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CYCLICAL SEDIMENTATION OF THE PENNSYLVANIAN PERIOD AND ITS SIGNIFICANCE[1]

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ABSTRACT

The Pennsylvanian strata of western Illinois exhibit a cyclical repetition of beds as follows: (1) sandstone and sandy shales, (2) underclay, (3) coal, and (4) marine limestones and shales. Each cycle was initiated by uplift which was reflected first by erosion and later by continental deposition of clastic materials. This was followed by a long period of stability during which weathering developed a typical poorly drained profile of weathering, now represented by underclay. Then peat, later transformed to coal, accumulated in more or less extensive swamps. These conditions were terminated by subsidence so that the area was inundated by a shallow sea in which marine strata were deposited until uplift brought the cycle to a close.

The cyclical repetition of beds is regional rather than local, and analysis of the conditions necessary for the formation and preservation of such strata over broad areas furnishes the basis for a reconstruction of the physiography of the Pennsylvanian period. The conception of widespread sedimentary cycles provides new criteria for correlation in Pennsylvanian areas, as a definite succession of strata not dependent upon certain key horizons is established. It also furnishes a new basis for paleontologic studies, since faunules restricted to different habitats may be grouped with regard to definite marine invasions and an approximation of the total marine fauna of each invasion may be obtained.

INTRODUCTION

Detailed geologic investigations in western Illinois, which have been conducted during the last few years by various members of the State Geological Survey, and reconnaissance studies in other areas, have revealed many facts concerning the relationships which commonly exist between the various strata in the Pennsylvanian system. Generalizations based upon these facts have led to the

[1] Published with the permission of the Chief, Illinois State Geological Survey.

development of a working hypothesis by which the stratigraphic succession may be explained and the physiography of the Pennsylvanian period interpreted. Although most of these facts have been noted by previous workers and although most of the inferences derived from them have been previously stated, still they have never been treated before in a comprehensive manner nor followed to a logical conclusion.

Like most hypotheses, this will inevitably be amended in the light of future investigations, but the new conceptions concerning Pennsylvanian conditions which it entails promise achievement and refinement in stratigraphic interpretation and correlation far beyond that which has resulted up to this time. The hypothesis of cyclical sedimentation has already proved its value in the detailed stratigraphic studies conducted in western Illinois. The extent to which it is applicable is not fully known, but with slight modifications it may be possibly extended to apply to the Pennsylvanian deposits in the entire interior of North America. With these points in view, the hypothesis is presented in the hope that geologists working in other areas of Pennsylvanian strata will consider their problems in its light and will observe and record the data which are significant and essential to the study of the Pennsylvanian problem in its broadest aspects.

I. THE CYCLE—ITS NATURE

PREVIOUS RECOGNITION

In 1912 Udden[1] subdivided the Pennsylvanian strata exposed in the Peoria quadrangle, Illinois, into four series of beds each of which included "four successive stages, namely: (1) accumulation of vegetation; (2) deposition of calcareous material; (3) sand importation; and (4) aggradation to sea level and soil making" (Fig. 1). This clear exposition of cyclical sedimentation and its possible significance in the field of correlation and interpretation of Pennsylvanian stratigraphy has received practically no attention from geologists.

Stout[2] has recognized that in Ohio certain types of strata, notably

[1] J. A. Udden, "Geology and Mineral Resources of the Peoria Quadrangle," *U.S. Geol. Survey Bull. 506* (1912), pp. 47–50.

[2] W. Stout, "Coal Formation Clays of Ohio," *Ohio Geol. Survey*, Ser. 4, *Bull. 26*, chap. vii (1923), pp. 533–68.

underclays, coals, and limestones, bear consistent relationships to each other, and he has developed a cyclical theory for the formation of underclays. Again, the possible stratigraphic importance of the repetition of beds has not been realized, and this consideration has not been carried to a logical paleophysiographic conclusion.

OTHER GEOLOGICAL CYCLES

The cycles (or rhythms)[1] which punctuated geologic time have been considered in some detail by Barrell,[2] who wrote,

> Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-mark, to those long deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras.

Many examples of cyclical change might be drawn from geologic history. Among the most conspicuous are the Pliocene-Pleistocene diastrophic cycles which resulted in sedimentation upon the Atlantic coastal plain and erosion along the adjoining river systems, and the climatic cycles of the Pleistocene, which caused the alternate extension and recession of the great continental glaciers.

UNCONFORMITIES WITHIN THE PENNSYLVANIAN

Another equally important fact, which has been greatly neglected, is the occurrence of unconformities within the Pennsylvanian deposits. Such an unconformity in Illinois was first recognized by Worthen[3] in the Peoria district where coal No. 5 is cut by channels filled with sandstone. Subsequent observers have reported similar unconformities at other Pennsylvanian horizons in different parts of the state, and Savage[4] has proposed to utilize such breaks in the sedimentary series as more natural boundaries between the Pottsville, Carbondale, and McLeansboro formations than the coal beds which have been so long employed for this purpose.

[1] *Cycle* seems to be the better term, as it implies simply recurrence, repetition, or a return to the starting-point, while *rhythm* includes also a time consideration, such as regular or measured movements. Geological phenomena were repeated at more or less irregular intervals.

[2] J. Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. Am.*, Vol. XXVIII (1917), pp. 745–904.

[3] A. H. Worthen, "Geology of Peoria County," *Geol. Survey Ill.*, Vol. V (1873), p. 242.

[4] T. E. Savage, "Significant Breaks and Overlaps in the Pennsylvanian Rocks of Illinois," *Am. Jour. Sci.*, Ser. 5, Vol. XIV (1927), pp. 307–16.

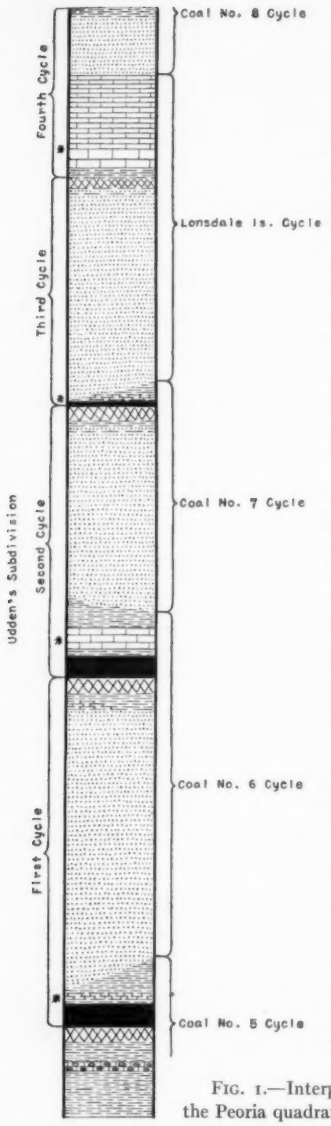

FIG. 1.—Interpretation of Udden's generalized section for the Peoria quadrangle. Scale 1 inch to 40 feet.

Similar unconformities have been noted in other states. In Missouri, the Moberly and Warrensburg channels are outstanding examples.[1] They occur abundantly also in the Coal Measures of the Appalachian basin and are casually mentioned in many reports: "The sandstone [Morgantown] reaches the Ames horizon and replaces the limestone over limited areas. In such instances there is a basal conglomerate";[2] "The disconformity at the base of the Lower Massillon sandstone at many places is marked as it replaces many feet of other strata [coals, clays, limestones, and shales] in a short distance";[3] "It [Mahoning sandstone] immediately overlies the Upper Freeport coal and often cuts out that seam";[4] "It [Freeport sandstone] may in some instances replace the coal [Upper Kittanning]. . . . . It has indeed

[1] H. Hinds and F. C. Greene, "The Stratigraphy of the Pennsylvanian Series in Missouri," *Missouri Bur. Geol.*, Ser. 2, Vol. XVIII (1915), pp. 91–106.

[2] D. D. Condit, "Conemaugh Formation in Ohio," *Ohio Geol. Survey*, Ser. 4, *Bulletin 7* (1912), p. 25.

[3] W. Stout, "Geology of Muskingum County," *ibid.*, *Bulletin 21* (1918), p. 60.

[4] C. Butts, "Economic Geology of the Kittanning and Rural Valley Quadrangles, Pennsylvania," *U.S. Geol. Survey Bulletin 279* (1906), p. 39.

been observed to begin even below the Darlington coal."[1] Similar unconformities are not uncommon in the English coal fields, as "large areas have been proved to exist, where the coal has been removed by wash-outs which have occurred at various horizons in the Middle and Lower Coal-Measures."[2]

Recent observations in Illinois indicate that unconformities within the Pennsylvanian system are more numerous than has been suspected. Detailed areal studies reveal that most massive sandstones lie unconformably upon subjacent beds, although this relation is rarely apparent in single outcrops. The evidence is so abundant that the generalization naturally follows that every massive sandstone lies unconformably upon the beds below.

FORMATIONS AND FORMATION BOUNDARIES

It has long been the custom to subdivide the strata of the Pennsylvanian system at prominent coal beds, because such beds are comparatively easy to trace and correlate. Udden[3] accordingly divided his section in the Peoria district at the coals. However, according to the accepted practice of stratigraphy, subdivisions of geologic time are separated by periods of instability, and as there is no evidence that any marked diastrophism occurred between the deposition of the beds below the coal and the development of the underclay, nor between the development of the underclay and the accumulation of peat, it does not seem advisable to use either the base of the underclay or the base of the coal as a series or formation boundary.

It is now proposed that each cyclical repetition of beds be considered a formation of the Pennsylvanian system. In each cycle there were two times when diastrophism was active: namely, (1) at the close of the period of peat accumulation when subsidence resulted in extensive transgression by the sea, and (2) before the development of the unconformity beneath the sandstone when uplift occurred and the sea withdrew from its shallow basin. The first probably represents the greater amount of local vertical movement, because in an

[1] L. H. Woolsey, "Economic Geology of the Beaver Quadrangle, Pennsylvania," *U.S. Geol. Survey Bulletin 286* (1906), p. 13.

[2] F. E. Middleton, "On the Wash-outs in the Middle Coal-Measures of South Yorkshire," *Quart. Jour. Geol. Soc. London*, Vol. LXI (1905), pp. 339–44 (illustrated).

[3] J. A. Udden, *op. cit.*

area of deposition subsidence must exceed uplift, but this horizon is unsuitable for a formation boundary, because marine beds do not succeed all of the coals in most areas. On the other hand, the unconformities—although more or less local in development—may be present and conspicuous even in areas not subjected to marine submergence. Also, as they are uneven surfaces, mapping of them reveals many interesting and significant features that would otherwise escape notice.

THE TYPICAL FORMATION

If Udden's section in the Peoria district[1] be subdivided at the bases of the sandstones, each series of beds starts with an unconformable sandstone below, contains an underclay and coal horizon in the middle, and continues above with limestone and shale. Such a series of beds is considered to be a typical Pennsylvanian formation, whose counterpart may be observed in almost every section from the bottom to the top of the system as developed in western Illinois.

In detail, the typical Pennsylvanian formation is composed of the following members:

Marine	8.	Shale, containing "ironstone" bands in upper part and thin limestone layers in lower part
	7.	Limestone
	6.	Calcareous shale
	5.	Black "fissile" shale
Continental	4.	Coal
	3.	Underclay, not uncommonly containing concretionary or bedded fresh-water limestone
	2.	Sandy and micaceous shale
	1.	Sandstone
		Unconformity

The succession of beds at any particular locality may be incomplete, or some members may be poorly developed owing to more or less local conditions. In most of such cases the absent or underdeveloped member appears at its proper position in the formation at other places. Such deviations from the typical formation as well as the rare introduction of additional members are not considered here, as they do not vitiate the essential principle and probably they can be logically explained when more detailed observations have

[1] *Ibid.*

been made. These irregularities in the formations are commonly confusing, but when the essential principle that the strata occur in a definite order, which is repeated many times, is once understood, almost any Pennsylvanian section may be readily subdivided into its component formations.

THE OHIO SECTION

Formations exhibiting cyclical repetition of beds similar to those which are so well developed in Illinois may be recognized readily in other states. In the generalized geologic sections for the Pottsville, Allegheny, and most of the Conemaugh series published in certain of the more recent *Bulletins* of the Ohio Survey,[1] the formations are distinct and easily separated (Fig. 2). However, distinctive marine horizons are lacking in the upper Conemaugh and Monongahela series, and it is difficult to interpret the published descriptions of this part of the section which is made up almost entirely of continental deposits. Of the forty-two formations indicated, a few, such as that including the Lower Kittanning coal, may be composite. Apparently the fossiliferous beds of the Brush Creek horizon fall within two formations (Nos. 22 and 23), but these are not very sharply differentiated.

This interpretation of the Ohio section is only tentative, as workers familiar with this area will probably find it necessary to make numerous alterations. It is presented here in order to establish the remarkable similarity of the Pennsylvanian sections in Ohio and Illinois and because the various members have been traced more consistently throughout Ohio than in Illinois. Most of the members in Ohio are very widely distributed, and there can be little doubt that nearly all of the Ohio formations are characteristically developed through the entire southeastern part of that state.

INADEQUACY OF MANY PUBLISHED SECTIONS

Many published geologic sections of Pennsylvanian strata are inadequate for subdivision into their component cyclical formations.

[1] D. D. Condit, "Conemaugh Formation in Ohio," *Ohio Geol. Survey*, Ser. 2, *Bulletin 17* (1912); W. Stout, "Geology of Southern Ohio," *Bulletin 20* (1916); "Geology of Muskingum County," *Bulletin 21* (1918); H. Morningstar, "Pottsville Fauna of Ohio," *Bulletin 25* (1922); W. Stout, and R. E. Lamborn, "Geology of Columbiana County," *Bulletin 28* (1924); W. Stout, "Geology of Vinton County," *Bulletin 31* (1927).

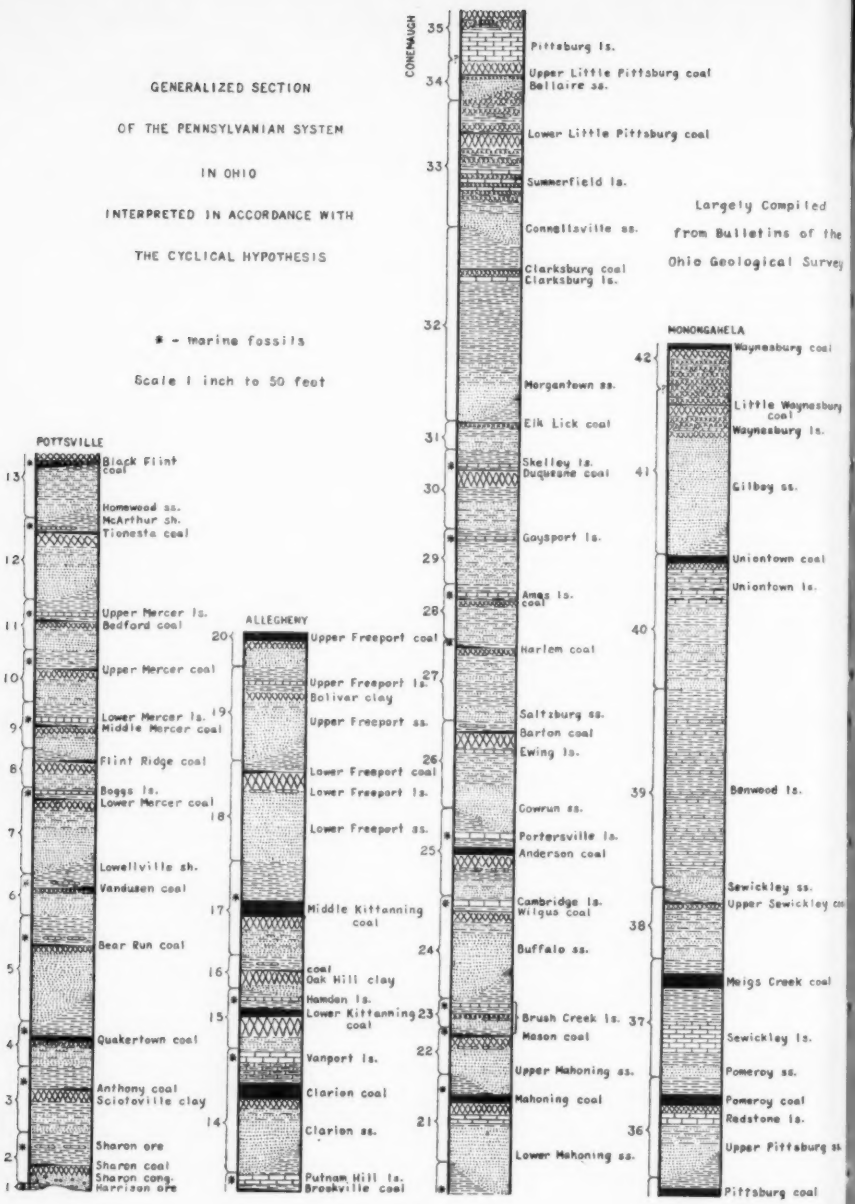
GENERALIZED SECTION
OF THE PENNSYLVANIAN SYSTEM
IN OHIO
INTERPRETED IN ACCORDANCE WITH
THE CYCLICAL HYPOTHESIS
* - marine fossils
Scale 1 inch to 50 feet
Largely Compiled
from Bulletins of the
Ohio Geological Survey
POTTSVILLE
ALLEGHENY
CONEMAUGH
MONONGAHELA
Black Flint coal
Homewood ss.
McArthur sh.
Tionesta coal
Upper Mercer ls.
Bedford coal
Upper Mercer coal
Lower Mercer ls.
Middle Mercer coal
Flint Ridge coal
Boggs ls.
Lower Mercer coal
Lowellville sh.
Vandusen coal
Bear Run coal
Quakertown coal
Anthony coal
Sciotaville clay
Sharon ore
Sharon coal
Sharon cong.
Harrison ore
Upper Freeport coal
Upper Freeport ls.
Bolivar clay
Upper Freeport ss.
Lower Freeport coal
Lower Freeport ls.
Lower Freeport ss.
Middle Kittanning coal
coal
Oak Hill clay
Hamden ls.
Lower Kittanning coal
Vanport ls.
Clarion coal
Clarion ss.
Putnam Hill ls.
Brookville coal
Pittsburg ls.
Upper Little Pittsburg coal
Bellaire ss.
Lower Little Pittsburg coal
Summerfield ls.
Connellsville ss.
Clarksburg coal
Clarksburg ls.
Morgantown ss.
Elk Lick coal
Skelley ls.
Duquesne coal
Gaysport ls.
Amas ls.
coal
Harlem coal
Saltzburg ss.
Barton coal
Ewing ls.
Gowrun ss.
Portersville ls.
Anderson coal
Cambridge ls.
Wilgus coal
Buffalo ss.
Brush Creek ls.
Mason coal
Upper Mahoning ss.
Mahoning coal
Lower Mahoning ss.
Waynesburg coal
Little Waynesburg coal
Waynesburg ls.
Gilboy ss.
Uniontown coal
Uniontown ls.
Benwood ls.
Sewickley ss.
Upper Sewickley coal
Meigs Creek coal
Sewickley ls.
Pomeroy ss.
Pomeroy coal
Redstone ls.
Upper Pittsburg ss.
Pittsburg coal

FIG. 2

In most cases this is due to the fact that they are not presented in sufficient detail. The grouping of a considerable thickness of strata as "sandstones and shales including thin coals and limestones" has been a common practice. Extreme variation, both vertical and lateral, has been considered a feature of general prevalence in Pennsylvanian deposits, but recent detailed studies prove that the formations as a whole remain remarkably uniform over wide areas, although individual members may thicken or thin and change greatly in character.

COMPARISON WITH CHESTER SERIES

The cyclical sedimentation which took place during the Pennsylvanian period is comparable to that which occurred in Chester time. In Illinois, the Chester series (Upper Mississippian) has been divided into sixteen alternating arenaceous and calcareous formations. A pair of these consisting of sandstone below and calcareous beds above constitutes a cycle. In one case,[1] a thin coal is widely present between the arenaceous and calcareous beds at a position precisely comparable to that occupied by the widespread Pennsylvanian coals.

The Chester series is transitional between the dominant limestone sedimentation of the earlier Paleozoic in the Mississippi and lower Ohio Valleys and the dominantly clastic sediments of the Pennsylvanian. A cyclical alternation between sandy and calcareous beds is well developed in the Chester and most of these units have been traced continuously from southwestern Missouri, across southern Illinois, and into western Kentucky, and it is probable that additional investigation will show that some of these are sharply differentiated and practically continuous as far south as Alabama. It is not unlikely that the cycles of the succeeding Pennsylvanian period were produced by similar changes in conditions which were likewise effective throughout extensive areas.

EXTENT OF CYCLES

It is obvious that the repetition of a certain series of beds reflects a similar repetition of a certain series of conditions. It is important to ascertain whether these conditions were prevalent contemporaneously throughout wide areas or were only local, as upon this de-

[1] J. M. Weller, "The Geology of Edmonson County," *Kentucky Geol. Survey*, Ser. 6, Vol. XXVIII (1927), pp. 121–22.

pends entirely the usefulness of the conception of cyclical sedimentation.

Extent of coal beds.—It has been long known that certain individual coal beds are continuous over extensive areas. The Pittsburg coal has been commonly cited as an outstanding example, estimates of its proved extent ranging from 6,000 to 8,000 square miles.[1] In the southern half of Illinois, a workable thickness of the Herrin (No. 6) coal is known to be present throughout an area of about 8,000 square miles, in addition to which a considerable territory remains unexplored. In the northwestern part of the Illinois basin, a coal that is probably the equivalent of this bed is extensively developed, so that an estimate of 10,000 square miles for a single seam in Illinois is considered conservative.[2] There is also little doubt that this same seam is extensively developed in Indiana and western Kentucky, which accordingly increases its estimated area. Less imposing figures might be quoted for other coal beds.

The thickness or quality of a coal is immaterial in the study of the stratigraphic succession; it is the position or horizon of the seam that is important. The figures given in the foregoing apply only to continuous developments of workable coal. If the areas in which coal of unworkable thickness is present, and those in which its horizon is indicated only by an underclay and dark shale be included, the figure for the areal extent of its horizon would be much larger. The facts that the Pittsburg coal is mined at widely distant localities in Pennsylvania, Ohio, West Virginia, and Maryland and that a thinner development of it has been recognized in outcrops and well records at many intervening places makes it fairly certain that the *horizon* of this coal is practically continuous throughout the Appalachian basin except where it has been cut out by intra-Pennsylvanian or by more recent erosion.

Extent of limestones.—The limestones of the Coal Measures constitute some of the most conspicuous and important horizons. Recent *Bulletins* published by the Ohio Survey[3] report in some detail

[1] I. C. White, "Report on Coal," Vol. II, *West Virginia Geol. Survey* (1903), pp. 166, 384.

[2] Estimates by G. H. Cady.

[3] D. D. Condit, "Conemaugh Formation in Ohio," *Ohio Geol. Survey*, Ser. 4, *Bulletin 17* (1912); H. Morningstar, "Pottsville Fauna of Ohio," *Ohio Geol. Survey* Ser. 4, *Bulletin 25* (1922).

on the occurrences of the Pottsville and Conemaugh limestones throughout that state. These beds occupy definite positions in the geologic section and some of them are widely distributed in West Virginia, and extend into Pennsylvania, Maryland, and eastern Kentucky. One of the most important is the Ames limestone (middle Conemaugh), which is not only widespread in Ohio but is also extensively developed in West Virginia and Pennsylvania and even continues as a marine bed into Maryland.[1] The Upper and Lower Mercer limestones of the Pottsville are very persistent and occur almost uninterruptedly along the whole length of the Pennsylvanian outcrop in Ohio as well as extending into neighboring states.

It seems probable that the rare limestones observed in Tennessee[2] and Alabama[3] may be the exact equivalents of certain of the lower Pottsville limestones in Ohio, and other fossiliferous horizons (five in Tennessee[4] and four in Alabama[5]) may also represent southern continuations of marine stages which are better known farther to the north.

Owing to low relief and thick glacial drift, the details of the Pennsylvanian section in Illinois are not so well known as they are in the northern portion of the Appalachian basin. Some of the limestone beds in Illinois, however, are known to be very persistent, as, for example, the "Fusulina limestone" cap-rock of the Herrin (No. 6) coal, which overlies this seam quite uniformly throughout the wide area in which it is known to occur.

In the Western Interior basin, where the marine beds are even more important than they are farther east, the lateral extension of various comparatively thin strata is still more striking and "there is increasing evidence of remarkable lateral persistence of various stratigraphic units."[6] For example, the beds assigned to the Hen-

[1] C. K. Swartz, W. A. Price, and H. Bassler, "Coal Measures of Maryland," *Bull. Geol. Soc. Amer.*, Vol. XXX (1919), pp. 567–96.

[2] J. M. Safford, *Geology of Tennessee* (1869), p. 367.

[3] J. Square, "Report on the Cahaba Coal Field," *Alabama Geol. Survey* (1890), p. 4.

[4] L. C. Glenn, "The Northern Tennessee Coal Field," *Tennessee Div. Geol. Bulletin 33B* (1925), pp. 23, 28, 34–36, 60, 134–36, 167, 227, 311, 316, 319, 330–32, 373, 426.

[5] C. Butts, "Geology of Alabama: The Paleozoic Rocks," *Alabama Geol. Survey Special Report 14* (1926), p. 213.

[6] R. C. Moore, "Environment of Pennsylvanian Life in North America," *Bulletin Amer. Assoc. Pet. Geol.*, Vol. XIII (1929), p. 479.

rietta formation have been traced with little modification from Oklahoma northeastward across Kansas and Missouri into Iowa, and a recent reconnaissance by Mr. J. B. Knight and the writer has served to indicate that these beds are probably exactly equivalent to certain strata in western Illinois (Fig. 3). This group of beds is easily identified by one of the most characteristic faunal assemblages in the Pennsylvanian system. Numerous other Pennsylvanian horizons are extensively persistent.[1]

Thin horizons in Illinois.—Recent work in the western part of Illinois by members of the State Geological Survey, of whom Dr. H. R. Wanless deserves particular mention, has proved that many individual horizons, some of which are only a few inches thick, are remarkably persistent. Such beds are not only easily recognized at scattered outcrops by lithologic and faunal peculiarities but also have been actually traced for long distances.

Conclusion.—The great lateral extent of many horizons in the Pennsylvanian system strongly supports the expectation that the cyclical formations of which these horizons are members may retain their individuality throughout areas of equal extent.

CORRELATION

Stratigraphic possibilities.—The problem of Pennsylvanian correlation has always been difficult. Dependence usually has been placed on certain lithologic characters of one or two closely associated beds. Coals and limestones have been relied upon, but coals thicken and thin, change in character, and not uncommonly pinch out entirely, and many limestones vary greatly within small areas, grade into calcareous shales, or perhaps are cut out by unconformities, so that uncertainty is introduced. However, if the hypothesis of widely extensive cyclical sedimentation is established, a *group* of beds may be used for correlation. Its thickness makes it easier to trace and the change in character, or complete absence of any particular member, creates no great perplexity.

Paleontologic possibilities.—As each cycle includes an advance and retreat of the sea, as will be set forth in some detail later,

[1] E. Haworth and J. Bennett, "Special Report on Oil and Gas," chap. iii, "General Stratigraphy," *Univ. Geol. Survey Kansas*, Vol. IX (1908), pp. 57–77; H. Hinds and F. C. Greene, "The Stratigraphy of the Pennsylvanian Series in Missouri," *Missouri Bur. Geol.*, Ser. 2, Vol. XIII (1915); G. E. Condra, "The Stratigraphy of the Pennsylvanian System in Nebraska," *Nebraska Geol. Survey*, Ser. 2, *Bulletin 1* (1927).

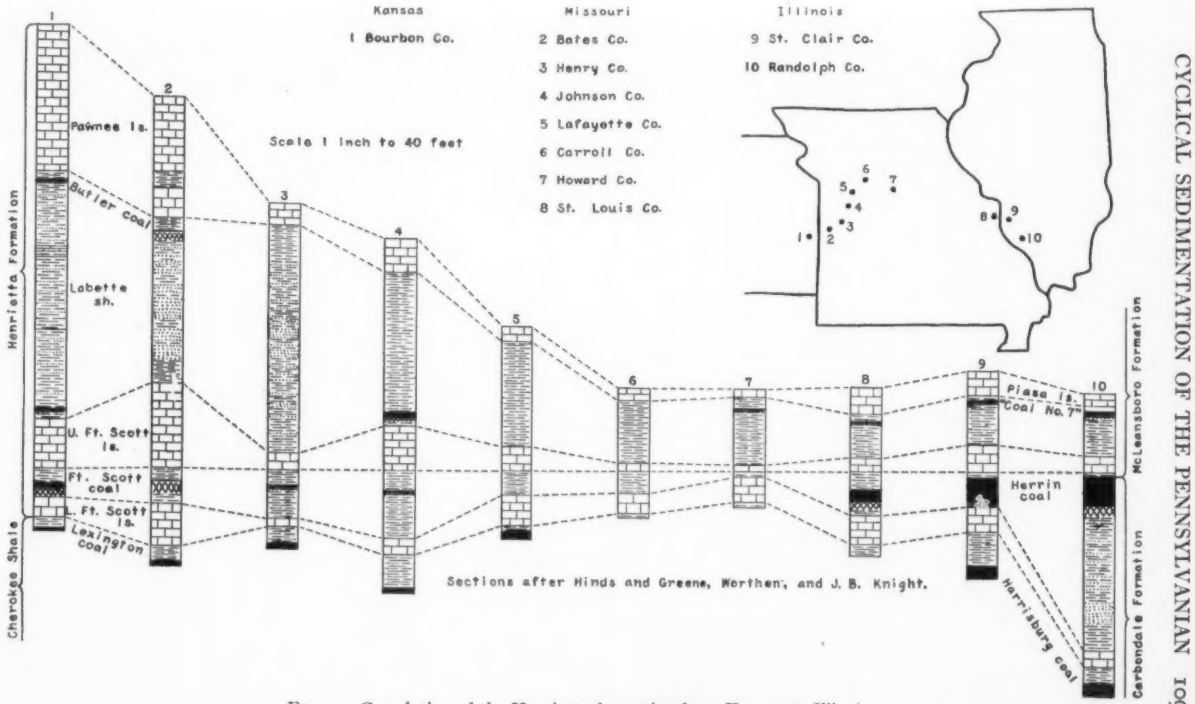

FIG. 3.—Correlation of the Henrietta formation from Kansas to Illinois

paleontologic studies may be logically based upon the cyclical formations. Heretofore, invertebrate fossils have given little aid in the precise correlation of Pennsylvanian strata. Many species were so restricted to certain habitats that few collections of Pennsylvanian fossils furnish a representative fauna. On the other hand, the more adaptable forms which are found associated with various types of sediments are nearly all long-range species and consequently are of little value to the stratigrapher. Therefore, the faunules which are obtained from beds lithologically similar, even though widely separated stratigraphically, are likely to resemble each other more closely than do practically contemporaneous faunules from different types of sediment.

However, if the various faunules of a single cycle are determined and combined, an approximation of the total marine fauna inhabiting the sea at the time of a single advance may be obtained. When such information for the various cycles has been gathered and is compared, it will probably reveal that certain species, varieties, or assemblages can be relied upon as guide fossils for the different formations.

Conclusion.—If the hypothesis of regional cycles be established, it will be possible to set up, in various widely separated Pennsylvanian areas, general geologic sections each of which is subdivided into a succession of comparable formations, and with the aid of paleontology these should be subject to precise correlation. Thus it should be possible to make definite, detailed correlations between the Pennsylvanian strata in Missouri-Kansas, Illinois, and Ohio, an accomplishment which has been heretofore impossible.

II. THE CYCLE—ITS INTERPRETATION

PHYSICAL ASPECTS OF NORTH AMERICA

The basin in which the Pennsylvanian sediments were deposited was bounded on the east and south by Appalachia and Llanoris, a newly upraised belt of highlands, and by the relatively low Canadian positive area upon the north. This broad basin was interrupted by the Cincinnati anticline, which was not a very important structural feature at the time, and by the Ozark dome which was not high enough to contribute any considerable amount of sediment, but which stood sufficiently above the basin of deposition that little

sediment was laid down upon it, at least during the first half of the Pennsylvanian period. The conditions to the west cannot be satisfactorily determined because the Pennsylvanian beds are buried beneath younger sediments. There is no evidence of any marine connection to the northwest or north, but it is clear that an unobstructed passage existed to the southwest, and it is probable that the later marine invasions which periodically submerged the interior of the continent advanced from this direction.

FORMER EXTENT AND SOURCE OF SEDIMENTS

Prevailing opinion.—There is a tendency to associate the original depositional limits of a geologic formation with the boundaries of its present occurrence, but such an idea is untenable unless there is definite evidence to substantiate it. Perhaps the dominantly clastic nature of Pennsylvanian strata, which does not indicate typical marine conditions, has led so many workers to assume that the present boundaries of the Pennsylvanian strata have been eroded back only a short distance from the original limits of their extent and as a result continental sedimentation has been generally mistaken for littoral.

Paleontologic evidence.—The Pennsylvanian strata of the interior of North America are confined to four structural basins, each of which is entirely separated from all of the others. Yet certain beds in each of these areas carry marine fossils. This proves that all of the basins were connected with the sea at various times during the Pennsylvanian period. The fossils of each area are similar and for the most part specifically identical, which shows that they were derived from the same source. Therefore, there can be no doubt that all of these areas were formerly connected.

Petrographic evidence.—In the literature are many references to the source of the Pennsylvanian sediments, but apparently this matter has never been especially investigated. Petrographic studies of certain Pennsylvanian sandstones in western Illinois by R. S. Poor and H. B. Willman has revealed the presence of unaltered feldspars and ferromagnesian minerals in greater or less abundance. These minerals show that the Pennsylvanian sands were derived from areas of igneous rock which were undergoing erosion sufficiently rapid that such minerals were not completely decomposed. Grains

of characteristic metamorphic minerals, except garnet, are absent or very rare.

The area of Pennsylvanian sedimentation was bounded by regions of crystalline rocks upon the north, east, and south. It is improbable that the Canadian Shield, during the Pennsylvanian period, was a mountainous area such as would have produced sands containing undecomposed feldspars, etc. Therefore, the petrographic character of the Pennsylvanian sandstones points strongly toward Appalachia and Llanoris as their source. Other evidence supports this conclusion. Many writers have pointed out that the various divisions of the Pennsylvanian system east of the Mississippi River increase in thickness as Appalachia is approached. The quartz pebble conglomerates, which are so common in the Pottsville of the Appalachian, and the southeastern part of the Eastern Interior basins, are similar to those which were deposited in the Appalachian trough in the Devonian and Mississippi periods, but it was not until Pennsylvanian time that they were carried out into the interior of the continent as far as western Kentucky and southern Illinois. It is also significant that, in general, the size of the pebbles increases eastwardly. A careful study of the cross-bedding and current-ripple marks of the Pennsylvanian sandstones should reveal the direction of the currents from which the sands were deposited.

Conclusions.—These facts indicate that the clastic Pennsylvanian sediments, at least as far west as Illinois, were derived from the highland regions of Appalachia and that the areas of Pennsylvanian strata, now isolated, were originally connected. It is probable that the structural basins in which the Pennsylvanian sediments of the interior now exist are very largely the result of warping which occurred at the close of the Paleozoic era, and that Pennsylvanian strata originally extended as an unbroken blanket far beyond their present limits. Subsequent to post-Paleozoic warping, erosion removed all or a large portion of these beds over wide areas, and they are preserved only in the down-warped basins.

Although small quantities of sedimentary material were undoubtedly derived from other sources, by far the greatest part of the Pennsylvanian sediments, at least those as far west as Illinois, was derived from Appalachia. This highland region included at least the

area of the present Piedmont Plateau and the adjoining belt eastward to the outer edge of the continental shelf (Fig. 4). It is significant that this area is widest at the south, where the lower Pennsylvanian sediments are thickest.

PENNSYLVANIAN SEDIMENTATION

In early Pennsylvanian time it is possible that periodic invasion of the sea extended up the Appalachian Valley from the south, reaching Illinois later than areas to the east, as the lower marine horizons of Ohio are believed to be older than any known in Illinois. It is very unlikely that marine connection with the Gulf of Mexico, by way of the Mississippi Valley, was cut off early in the Pennsylvanian period, because the only other possible connection was the trough lying between Llanoris and Ozarkia, and the sediments in it do not indicate that it was a seaway at this time, as they are clastic and almost entirely barren of marine fossils, except for the Morrow fauna (lowest Pottsville), which is older than any of the faunas that are known to the east or north.

The oldest conspicuous marine horizon of western Illinois is the limestone cap-rock above the Rock Island (No. 1) coal. It occurs at a horizon which is approximately equivalent to the Lower Mercer limestone of Ohio. The deposition of this bed appears to mark the first possible extensive marine connection between Illinois and the Western Interior basin. Direct connection between the Illinois basin and the Gulf of Mexico probably existed until this time, but subsequent marine invasions may have entered Illinois from the west rather than the south. The close similarity of fauna in higher horizons in Illinois and in Missouri, Iowa, Kansas, Oklahoma, and even Texas is evidence that in Allegheny and subsequent Pennsylvanian times the main invasions of the epicontinental seas were from the west and a direct connection with the gulf by way of the Mississippi Valley was no longer required.

If the Mississippi Valley connection was blocked in late Pottsville time, as seems likely, this was probably accomplished by sedimentation rather than by diastrophism. Erosion in southern Appalachia was very rapid, as shown by the coarse and unweathered sands which were derived from it to form a great delta and alluvial-plain

FIG. 4.—Paleogeographic map of North America, showing the total area submerged at one time or another by the Pennsylvanian seas. The Ozark Dome and Cincinnati Anticline, which were formerly covered by Pennsylvanian sediments, are outlined with dots.

deposit.[1] Similar processes operating on a grand scale in northern Llanoris produced the enormously thick Pennsylvanian clastics in Arkansas, filling the trough between Llanoris and Ozarkia, and probably spreading out eastward to connect with the southern Appalachian deposits. Possibly thus the Mississippi embayment was cut off.

The physical conditions which prevailed during the Pennsylvanian period in Eastern North America—a broad, interior lowland bordered by highlands undergoing rapid erosion—were ideal for the development of a series of confluent alluvial fans which later merged into a great alluvial plain stretching far westward from Appalachia. These continental deposits and the marine beds that record the periodic flooding of this area by the sea make up the strata of the Pennsylvanian period.

THE CYCLE OF DEPOSITION

The physiographic cycle of erosion is a concept familiar to all geologists and its effects are readily discerned on many land surfaces, but the material removed during the course of these cycles of erosion was deposited rarely in such positions that its connection with them may be observed. On the other hand, the older clastic sediments have been uplifted, deformed, and dissected so that they may be studied at many places, but the areas of erosion from which these sediments were derived are no longer preserved. In neither case can the intimate but variable relations which undoubtedly exist between an area of erosion and its corresponding area of deposition be studied directly. However, for each cycle of erosion in the uplands there should be a cycle of deposition in the basin. The two types of cycles are antithetical but complementary. They are similar only in that each is controlled by baselevel, the erosion cycle cutting downward to baselevel and the depositional cycle building up to it.[2]

Cycles of deposition may be best observed in ancient delta or

[1] D. White, "Deposition of the Appalachian Pottsville," *Bulletin Geol. Soc. Amer.*, Vol. XV (1904), pp. 267–82.

[2] J. Barrell, "Rhythms and Measurements of Geologic Time," *Bulletin Geol. Soc. Amer.*, Vol. XXVIII (1917), pp. 746–809; J. E. Eaton, "The By-passing and Discontinuous Deposition of Sedimentary Materials," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. XIII (1929), pp. 713–61.

alluvial-plain deposits, where strata were laid down partly under continental and partly under marine environments. Barrell[1] wrote

> to simply determine in some regions some formations as fluviatile and others as marine does not complete the conceptions of the larger relations of each to the other, which is given by the theory of the growth and retreat of deltas.
>
> When such a conception is attained, the mind may look back at the complete geosyncline and view it as made of beds laid down on the one side by the land and on the other by the sea, each advancing into the other and dovetailing in intricate fashion, though one or the other may much of the time be absent, and when present seldom of equal development. Looking down through the depths of the solid rocks the surface of separation is seen to be generated by the ascent of the strand-line through the geologic ages, oscillating back and forth and often completely across the zone of sedimentation.

These remarks are particularly applicable to the Pennsylvanian system, which over large areas is made up of alternating continental and marine strata. A careful consideration of the various types of sediments which occur at remarkably consistent positions in the various Pennsylvanian formations and the conditions which were required for their formation and preservation leads to a clear picture of the physiographic history of the Pennsylvanian period. It is possible that with this knowledge the stratigraphic sections in other areas where the succession of events is less apparent may be deciphered.

UNCONFORMITIES

The typical cyclical formation, as previously outlined, begins with an unconformity which separates the new formation from subjacent strata. This unconformity, which followed a period of marine sedimentation, was caused by regional uplift. The evidence for this conclusion will be presented later. Into this newly upraised plain, streams intrenched valleys, some of which have been traced long distances as, for example, the Moberly and Warrensburg channels in Missouri. In western Illinois channels from 80 to 100 feet deep were developed at at least two of these erosional stages. Such channels are not uncommonly several miles in width, and the sides of many of them are very steep. Small tributary channels have rarely been observed. It is highly improbable that such channels could have been eroded in the bottom of a shallow epicontinental sea, because

[1] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bulletin Geol. Soc. Amer.*, Vol. XXIII (1912), pp. 413–14.

upon the modern sea bottom even small channels are absent except in localities where current rather than wave action is unusually effective.[1]

The channels are now filled with sand or sandy shale and locally bear conglomerates in the lower portions. Some writers have explained such channel sandstones as being due only to lateral variation in sedimentation, but their true character is clearly apparent wherever the margins of the channels are exposed.

The erosion which produced these unconformities was fairly rapid and most of it in Illinois and adjacent areas was probably accomplished by streams whose waters were derived from distant sources. There was only slight weathering of the land surface either in or adjacent to the channels or upon the uplands where erosion was not active. Evidently the land surface was not exposed long enough for the development of a weathering profile.

One feature of many of the unconformities deserves particular mention. The sandstones which now fill the old channels not uncommonly rest more or less evenly upon the underlying coal beds. The channels were, therefore, cut downward not only through a considerable thickness of shale but also, in most cases, through a conspicuous limestone bed. The erosion which was capable of cutting through shale and limestone was checked at the coal bed, which was probably compressed peat at this time. Such occurrences, which are too numerous to be due to chance, indicate that the peat beds must have offered more resistance to erosion than the shales and limestones. This conclusion is verified by observations of an existing English peat bed which resists erosive action by a river so that it projects as a promontory.[2]

CONTINENTAL DEPOSITION

Causes.—The erosional unconformity was followed by aggradation. This reversal in the physiographic process was caused either by decreased gradient or overloading of the streams at their sources. There may have been (1) subsidence in the area of aggradation, (2)

[1] J. Barrell, "Criteria for the Recognition of Ancient Delta Deposits," *Bulletin Geol. Soc. Amer.*, Vol. XXIII (1912), pp. 427–28.

[2] E. W. Prevost and T. M. Reade, "The Peat and Forest Bed at Westbury-on-Severn," *Cotteswold Nat. Club Proc.*, Vol. XIV (1901).

uplift in the region from which the sediments were derived, (3) change in climatic conditions, or (4) a combination of these causes.

Climatic change,[1] especially affecting the amount or seasonal distribution of rainfall, must not be disregarded throughout this discussion. Its effect, however, is very difficult to evaluate. Additional rainfall might result in a greater amount of erosion or it might favor more luxuriant vegetable growth, which would serve as a protection against erosion. Also climatic change may have been purely cyclical and independent of changes in the physical features of the continent, or it may have resulted from such changes.

Without disregarding the possibility of climatic change, the reversal of the physiographic process from erosion to sedimentation may be satisfactorily explained by diastrophic movements. Thus the uplift which resulted in erosion may have been followed by continued uplift of considerable magnitude in Appalachia but less pronounced to the west. Erosion in the uplands would be accelerated, the streams would be overloaded and their excess sediments would be deposited upon the plains where erosion had been formerly active.

Nature of deposits.—Under such conditions the channels were quickly filled with sand and silt, after which the sediments were spread irregularly over practically the entire plain. The courses of the streams continually shifted. Temporary lagoons were first formed and later filled with sandy and micaceous silts. Aggradation continued until the surface of the plain had been built more or less uniformly up to baselevel.

This alluvial plain may be compared in a general way to the basin of the Ob River and its tributaries in Western Siberia,[2] which has an areal extent of over half a million square miles and is one of the largest unbroken lowland regions on the earth. It is almost entirely composed of alluvial materials brought down from the highlands of Central Asia and spread out to form a practically level plain, whose regional slope throughout wide areas is less than 1 foot per mile. However, alluviation is no longer taking place. The rivers

[1] J. Barrell, "Relations between Climate and Terrestrial Deposits," *Jour. Geol.*, Vol. XVI (1908), pp. 159–90, 255–95, 363–84.

[2] T. Belt, "The Steppes of Siberia," *Quart. Jour. Geol. Soc. London*, Vol. XIII (1874), pp. 490–98; *Encyclopedia Britannica*, 14th ed. (1929), Vol. XIX, p. 684.

have been rejuvenated, probably since glacial times, and are now flowing in intrenched valleys.

The arenaceous strata that comprise the lower portions of the Pennsylvanian cyclical formations are widespread but thin. In Illinois they rarely achieve a thickness of 100 feet even in the channel zones, and elsewhere they are commonly from 5 to 10 feet thick. These figures indicate that the baselevel of deposition was not greatly displaced upward. For the most part these strata have the character of top-set delta beds.

The clastic materials deposited upon the great Pennsylvanian alluvial plain are coarsest nearest Appalachia and become finer westward. Many of the arenaceous beds in Illinois appear to be typical sandstone but are composed largely of silt-sized grains.

It is probable that in most of the Pennsylvanian cycles aggradation was almost universal from Appalachia to the withdrawn epicontinental sea. Material not deposited upon the alluvial plain was carried into the sea and the coarser part spread out along the shore, while the finer settled far and wide upon its shallow bottom. Thus, although most of the arenaceous beds are believed to have been deposited under subaerial conditions, some similar material was probably also laid down under a truly marine but littoral environment.

Continental character.—The continental character of most Pennsylvanian sandstones and sandy shales is plainly written upon them. Their cross-bedded and current-rippled structure, their occasional mud cracks, and the abundant vegetable impressions and fragments are among their most conspicuous features, and their poorly sorted nature and rapid lateral variation are impressive on closer examination. The pebbles which are so common in some parts of the Pottsville series must have required fairly strong currents for their transportation. Littoral currents might have carried them long distances, but their wide distribution at certain horizons and their occurrence in erosional channels is strong evidence of their having been transported by streams.

Marine fossils rarely occur in the Pennsylvanian sandstones of the Eastern Interior or Appalachian basins, but thin films or lenses of coal are not uncommon. The absence of marine fossils is negative evidence; the coaly material might have been formed from vegeta-

tion washed into the sea, but still they strongly point toward a continental origin for the sandstones. Those rare arenaceous beds which contain marine fossils are possibly the shoreward facies of marine deposits contemporaneous with the aggradation of the alluvial plain.

CESSATION OF CONTINENTAL SEDIMENTATION

Causes.—The deposition of sands and sandy silts over the interior of the continent ceased, not only because the alluvial plain was aggraded to baselevel but also because the supply of clastic material from Appalachia was cut off. The lack of sediment may be attributed to (1) peneplanation of Appalachia, (2) subsidence of Appalachia, or (3) change of climate.

Peneplanation.—The peneplanation of Appalachia would satisfactorily explain the lack of sediments. However, very long periods of time are generally considered necessary for the development of peneplains, and it is improbable that forty-two or more successive peneplanations should have occurred during the Pennsylvanian period alone.

Subsidence of Appalachia.—Subsidence of Appalachia would also terminate continental sedimentation upon the alluvial plain by reducing the gradient of the streams. It is not unusual for a rapid uplift of a positive area to be followed by a slighter, more gradual, compensating subsidence, and such reactions might have followed the periodic elevations of Appalachia during Pennsylvanian time. This possibility is supported by the not uncommon occurrence of lenticular non-marine limestones closely underlying coal beds of the upper part of the Pennsylvanian system in Ohio and also at numerous horizons in Illinois. Such limestones were probably deposited in local and shallow depressions ponded by a slight subsidence of Appalachia.

Change in climate.—It has been stated previously that the probable consequences of climatic changes are not known, but their possibilities cannot be ignored. A careful study and comparison of the plant remains found in the clastic continental sediments and the overlying carbonaceous beds might throw considerable light upon this phase of the problem.

UNDERCLAY FORMATION

Previous opinions.—The intimate association of Carboniferous coals and underclays is almost universal. This association, the character of the underclay, and the not uncommon occurrence of root markings in it have been considered, for many years, evidence that the underclay represents the soil in which the coal plants grew. More recently Stout[1] has shown that the thicknesses of associated coals and underclays bear no relationship to each other, and that the chemical compositions of underclays and coal ashes are strikingly similar. On the basis of these facts he contends that the underclay is not merely an old soil but that it is composed of insoluble sediments which slowly accumulated under conditions very similar to those which prevailed during the time of peat formation, except that the vegetable material decayed completely, instead of being preserved and later transformed into coal. Therefore, he considers that "the clay represents the accumulation of terriginous sediments and minerals from the plant ash, and the coals these with the addition of preserved carbon."

Recent observations.—In 1928 Drs. M. M. Leighton, H. R. Wanless, and A. C. Bevan observed an exposure of the underclay beneath the Herrin (No. 6) coal of the Peoria district, in which there were exhibited all zones of a characteristic poorly drained weathering profile,[2] as follows:

Coal
Underclay
1. Dark, humus-bearing clay, more or less laminated
2. Light, bleached, very plastic clay
3. Irregularly iron-stained clay
4. Calcareous clay, containing impure limestone nodules grading into
5. Unaltered silty, calcareous, shale

More recently Wanless has carefully examined many Pennsylvanian sections in western Illinois in which the underclays beneath a large number of different coal beds are exposed. He reports that in almost every case a poorly drained profile of weathering is at least suggested, and that in many places it is well developed.

[1] W. Stout, "Coal Formation Clays," *Ohio Geol. Survey*, Ser. 4, *Bulletin 26*, chap. vii (1923).

[2] M. M. Leighton and Paul MacClintock, "Weathered Zones of the Drift-sheets of Illinois," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 28 ff.

Interpretation.[1]—These observations supply very suggestive evidence that the underclays represent weathering profiles produced by long-continued exposure to atmospheric agents. The time required for their development, judged in the light of recent observations on the weathering profiles of the earlier Pleistocene drift-sheets to which they are comparable, was very great. Horizon 2 of the gumbotil profile on the Illinoian drift, which corresponds to the plastic clay horizon of the underclay, commonly attains a thickness of from $3\frac{1}{2}$ to 5 feet and is considered to have required from 100,000 to 200,000 years for its development.[2] The Pennsylvanian underclays, which rarely achieve greater thickness, were probably produced somewhat more rapidly as they were derived from more homogeneous and permeable materials without pebbles or boulders, and as the climate of the Carboniferous was probably such that ground-water circulation was not interrupted during certain seasons by freezing. The time required for the formation of an underclay, however, may have nearly equaled that during which all the sediments of the complete cycle accumulated.

The presence of an underclay in every cyclical formation is perhaps the most convincing evidence that the cycle of conditions was regional rather than local. It is highly improbable that the long periods of stability necessary for the development of weathering profiles with precisely identical relations to certain stages of sedimentation could have occurred at unsynchronized intervals in numerous local areas. Theoretically, therefore, the underclays should be the most important, most significant, and most persistent members of the cyclical formations. This is substantiated by field observation as the underclays persist more or less uniformly far beyond their accompanying coals and over areas in which the other members of the formations change markedly in character and thickness.

The land surface upon which the underclay developed was practically free from either erosion or deposition, although some

[1] Further studies of the underclays are planned by the Illinois State Geological Survey. These will include additional field observations and chemical and petrographic investigations.

[2] M. M. Leighton, personal communication.

local transference of the surface materials probably occurred. The shallow, local depressions in which fresh-water limestones had previously been deposited were partially filled by the inwash of small amounts of material from closely adjacent, slightly higher areas. At a few localities a persistent coal rests unconformably upon lower beds without an underclay. Such situations prove that at a few places local erosion actually occurred either during or after development of the underclay.

The local unconformities below certain persistent coals are more significant in that they show the underclay was not a soil developed by the action of the plants whose remains were later transformed into the coal. Apparently, the underclay was fully developed before peat accumulation began. This conclusion is substantiated by the fact that the roots of Lepidodendron and Sigillaria stumps, which have been preserved *in situ*, spread out laterally along or close to the surface of the peat bog as it existed at the time they lived,[1] instead of penetrating downward into the peat or underlying material. The laminated structure of most coals and the undisturbed clay partings that are common in them plainly indicate that the peat was undisturbed by the roots of plants growing above. Conditions in the lower layers of the peat were probably such that even the roots of the coal plants could not endure them.

The not uncommon occurrence of Pennsylvanian underclays without overlying coal beds is evidence that peat-bog conditions were not necessary for the development of underclays, nor were they produced later by sulphuric acid bearing solutions derived from the oxidation of pyrite in an overlying coal bed. On the other hand, the occurrence of coal seams without underclays, rare in the case of Pennsylvanian coals in Illinois, but of general prevalence in the post-Paleozoic coal fields of the Book Cliffs region in Utah[2] and probably elsewhere, proves that underclays are not necessarily developed below peat bogs. The fact that coals and underclays are not genetically related is shown also by the nature of the underclay itself and by the conditions necessary for the existence of a peat bog. The

[1] D. White, "The Origin of Coal," *U.S. Bureau Mines, Bulletin 38* (1913), p. 56.

[2] D. J. Fisher, personal communication.

weathering profile of the underclay was produced by the leaching and oxidizing action of descending ground waters, while stagnation of drainage and lack of oxidation are required for the occurrence of peat bogs. Finally, no profiles of weathering are known to have developed beneath either Pleistocene or recent peat bogs.[1]

COAL FORMATION

A great deal has been written on the formation of coal, particularly with regard to whether the vegetable matter from which it was produced grew in place or was transported. Practically everyone in this country, however, now agrees that the evidence is conclusive that the American Carboniferous coals were formed in place. Therefore, it is necessary only to consider the physical conditions which prevailed throughout the interior of the continent during the accumulation of the vegetable material which has been subsequently transformed into coal.

Plants undoubtedly grew upon the alluvial plain since the beginning of the cycle, but rapid sedimentation or adverse climatic conditions during its early part prevented any extensive or thick accumulations of peat. Coal partings or lenses occur in the sandstones at many places, but such deposits are thin and local. The humus-bearing layer in the upper part of the underclay indicates that vegetation grew during the long period while the weathering profile was being developed, but evidently conditions were still unfavorable for accumulation and preservation of peat.

The development of coal swamps was caused either by slight subsidence of the alluvial plain, still further reducing its gradient, or by increased rainfall which caused a luxuriant jungle growth to spring up. Certain areas were so situated that the very sluggish surface drainage was trapped by this tangled mass of vegetation, and they became extensive swamps in which peat accumulated. In other areas, more easily drained, conditions were changed little, the vegetation was more sparse, and as it died it decomposed, either producing only a layer of humus or leaving not even material of this nature Here and there in the swamps were more or less open bodies of stagnant water in which spore cases and pollen settled and were later transformed into cannel coal. Although peat did not accumu-

[1] M. M. Leighton, personal communication.

late over the whole of the alluvial plain, this surface represents an important coal horizon which is now marked by coal, black shale, or humus almost invariably present above the underclay.

Such a picture of enormous, discontinuous, but contemporaneous coal swamps extending from Kansas to Pennsylvania may be startling to one who has always considered them to have occupied a rather narrow belt along a shore line which gradually retreated owing to the filling up of the inland sea. However, this view is perfectly consistent with the cyclical hypothesis and satisfactorily explains the great extent of many important coal beds.

Extensive modern swampy areas comparable to those which existed during Pennsylvanian time are found in the circumpolar tundra, of which Alaska offers excellent examples.[1] The tundra is a more or less level but slightly undulatory region. It is carpeted with dense, luxuriant, dwarf vegetation as saturated with water as a sponge even on the steeper slopes. It is swampy, drainage is very poor, and many small lakes and ponds without outlets or inlets dot its surface, occurring not only in depressions but also on the hillsides. A layer of peat or humus is constantly accumulating by the death and decay of the vegetation, while other plants continue to grow above. This layer may attain considerable thickness; from 12 to 15 feet is not unusual and from 150 to 300 feet has been reported as exposed in a sea cliff on Eschscholtz Bay.

Russell was much impressed by the peat deposits of the tundra and wrote:

> So vast is the amount of vegetable material now imprisoned in the tundra of the North, that I venture to suggest that possibly some coal seams may have had a similar origin.
>
> This suggestion does not seem so very unreasonable when one remembers that except in the circum-polar tundra, deposits of vegetable matter are nowhere accumulating at the present day to anything like the extent or thickness required for the formation of coal fields like the one, for example, of which Pennsylvania still remains a remnant. Botanists will say at once, in opposition to this suggestion, that the flora of most of our coal fields, and especially those of Paleozoic age, indicate tropical or sub-tropical conditions. The flora of the tundra, however, like the plants of the Carboniferous, is essentially and characteristically cryptogamic. Two species of Equisetum, which may be con-

[1] I. C. Russell, "Notes on the Surface Geology of Alaska," *Bulletin Geol. Soc. Amer.*, Vol. I (1890), pp. 125–28.

sidered as representing the Calamites of former time, flourish with rank luxuriance over great areas along the Yukon.

If the tundra-fringed coast of Alaska should subside, the peaty layer with which it is covered would become buried beneath sands and clays, and form a stratum in every way favorable for transformation into lignite and coal.[1]

SUBMERGENCE

The period of emergence was brought to a close by rapid subsidence of the coal swamps, which resulted in a great transgression by the inland sea. The marine waters extended widely throughout the interior of the continent and opened a vast area for the colonization of marine organisms. These migrated from the southwest in great numbers and variety. The sea was shallow, as shown by the sediments which accumulated in it and the animals which lived upon its bottom. Conditions of turbidity and salinity varied greatly from place to place and the migrating marine organisms sought those habitats to which they were adapted. Thus faunules of quite different character existed contemporaneously in adjoining areas.

It is significant that, over broad areas not only in North America but also in other lands, the periods of peat accumulation were commonly brought to a close by marine inundation. In England marine conditions directly succeeded the formation of many peat beds,[2] and marine limestones are generously distributed throughout the Coal Measures of the Donetz basin in southern Russia. In regions where characteristically marine faunas are lacking, brackish water molluscs (commonly termed "non-marine") are in many cases to be found in the roof shales of the coal seams.[3] Such a parallelism between American and European Coal Measures stratigraphy suggests that the conditions and processes which prevailed throughout Upper Carboniferous time were essentially similar over large portions of the globe.

Black "fissile" shale.—The Pennsylvanian coal beds are commonly overlain by black "fissile" shale, termed "slate" by the

[1] *Ibid.*, pp. 127–28.

[2] G. Wild, "Lower Coal Measures of Lancashire," *Manchester Geol. Soc. Trans.*, Vol. II (1892), pp. 364 ff.

[3] J. H. Davis, "Zoning of the Coal Measures by Non-marine Lamellibranchs," *Congrès pour l'avancement des études de Stratigraphie Carbonifère (Heerlen, 1927) Compte rendu* (1928), p. 219.

miners. The formation of black shale of this kind has attracted the attention of numerous writers, but little is known concerning the conditions under which it accumulated. The Pennsylvanian black shales are marine, but the fossils which occur in them show that conditions were peculiar and almost invariably inhospitable to normal marine faunas.

As the black shales were the first deposits in the transgressing sea, it seems probable that they were laid down in very shallow water, but their finely laminated structure shows conclusively that the sea bottom was not subject to any great stirring by wave action. Unless the waves, which even gentle winds are capable of producing, were damped in some manner, this structure could not have been developed and preserved. Possibly lowly organized plants, such as marine algae, may have been present in sufficient abundance to prevent the development of waves, and when they died they left no other trace than the carbonaceous content of the shales. This carbonaceous matter cannot have been obtained by reworking of the upper portion of the peat bed as some of the black shales attain a considerable thickness without apparent decrease in carbon content above, and others are separated from the underlying coals by as much as from 40 to 50 feet of light gray, plant-bearing shales.

Calcareous shale and limestone.—The black shale is followed by lighter-colored, calcareous shale, which in most cases grades upward into limestone. This limestone and its associated calcareous shale ordinarily contain a varied fauna and indicate that normal, shallow marine conditions prevailed during their deposition. The Pennsylvanian limestones vary greatly in character. Some of them are earthy, shaly, or impure, but others are quite pure and dense and were largely produced by bacterial or chemical precipitation in clear water. Other beds are dominantly algal, but very few of them, except some thin layers in the shales, are composed largely of shells or shell fragments, corals, bryozoa, etc. It is evident that during the time of limestone deposition, comparatively little clastic material was being contributed by the land.

A number of limestones that are generally considered to be of fresh-water origin occur in the upper part of the Pennsylvanian system in Ohio and adjoining states of the northern Appalachian

region. These beds contain ostracods, worm tubes, and a few species of minute molluscs, but lack the remains of characteristic marine invertebrates. In general they should probably be considered to occupy positions corresponding to the non-marine limestones, which normally occur a short distance beneath the coal beds in the lower part of the system in that region and in Illinois. However, fish remains, which appear to be identical with some of those found in the marine limestones of Illinois,[1] occur in several of these beds, showing that brief marine connections did exist. Periodic marine extensions as far east as Ohio persisted even in Dunkard time, as a species of *Lingula* has been collected from shale overlying the Washington coal.[2]

Shales.—The Pennsylvanian limestones grade upward through highly calcareous shales to more or less silty shales in which there are thin layers of limestone, "ironstone," or sideritic concretions. These shales are commonly bluish or grayish in color, and vary from finely laminated to massive in structure. Some of them are micaceous, but few are arenaceous. Although fossils occur in great numbers in the lower part of these shales at some localities, most of the beds are entirely barren of remains of both animals and plants. A few marine fossils, chiefly molluscs, occur in the upper parts of such shales at a few places and an occasional limy or sideritic layer contains a varied fauna. Well-preserved leaf impressions are also rarely present in concretionary nodules. The few molluscan fossils which are contained in these beds indicate that they were deposited in the sea, but normal marine conditions were probably lacking during most of the time that they were accumulating.

The fact that such shales follow the limestones shows that for some cause clastic material was again being contributed by the land. This might have been due to slight uplift of Appalachia or to climatic change. During all of the time that had been required for the development of underclay and the accumulation of coal and limestone in the interior, Appalachia had been subject to weathering, and it is probable that the crystalline rocks exposed there were more or less

[1] J. J. Stevenson, "The Formation of Coal Beds, III," *Amer. Philo. Soc. Proc.*, Vol. LI (1912), p. 504.

[2] C. R. Stauffer and C. R. Schroyer, "The Dunkard Series of Ohio," *Ohio Geol. Survey*, Ser. 4, *Bulletin 22* (1920), p. 143.

decomposed to considerable depth. An uplift would have enabled erosion to act upon this material, which was prepared for easy removal, and if the uplift were slight, only the finest material would have been transported to the sea and spread out upon its bottom while the sands remained in place, or at most were removed no farther than the sea shore.

Similar results may have been achieved by climatic change, but the nature of the changes required is intangible and uncertain.

Nature of Pennsylvanian seas.—The extensive, shallow, landlocked seas of the Pennsylvanian period were probably almost tideless, as are modern landlocked seas, such as the Baltic and Mediterranean, to which they may be roughly compared, and consequently tidal currents or scour could not have been effective. Other currents, however, produced by rotation of the earth, winds, differences in temperature, and the inflow of terrestrial waters undoubtedly were present, but it is improbable that they achieved more than moderate velocity and therefore served merely for the transportation and dispersal of sediments over the sea bottom.

Wave action undoubtedly played an important part in molding the character of some of the Pennsylvanian beds. Many of the purer limestones are somewhat brecciated or conglomeratic. This texture is probably the result of wave action on the partially consolidated lime muds of the sea floor. Some of the shales are thick bedded and almost structureless, possibly owing to repeated stirring up by waves. As a whole, however, the results of wave action upon the marine beds of the Pennsylvanian system are not as conspicuous as might be expected in sediments deposited in such shallow seas. The climate of the Pennsylvanian period was equable over practically the whole world, so that meteorological conditions were probably rather uniform and violent winds and storms which characterize the modern world were absent. Consequently, wave action was probably not as effective at that time as it is today.

Under the conditions which existed in the epicontinental Pennsylvanian seas, the fresh terrestrial waters would not have been mixed readily with the saline waters of the embayment but would have gradually pushed the salt water backward away from the shore. Thus, fresh or only slightly brackish conditions probably prevailed

along the shore, merging through a transitional zone with the normal saline waters of the sea. In just this way the salinity of the modern ocean is greatly reduced near the mouth of a large river, such as the Mississippi or the Amazon. Under such circumstances a normal marine fauna should not be expected in the deposits of the fresh or brackish waters adjacent to the shore. An example of faunal changes resulting from such conditions may be seen in the Cambridge horizon of Maryland,[1] which contains marine species in the western outcrops, but to the eastward the fauna becomes meager, brackish-water forms appear, and finally the marine species disappear entirely. Such an explanation may also account for the few indications of marine life which have been observed in the upper Pennsylvanian beds in Ohio and West Virginia.

It seems likely that the fresh or brackish-water conditions which existed only adjacent to the shores during the time of limestone deposition were more widespread later while the overlying shales accumulated. Under these circumstances, the sea waters would not have been notably saline and therefore not capable of rapid flocculation, and the fine sediment would have been spread far and wide in the shallow waters. Such conditions also satisfactorily explain why the seas were largely inhospitable to normal marine life at these times.

UPLIFT

The cycle was brought to a close by uplift, and the whole sequence of events outlined in the foregoing was repeated.

At the beginning of this discussion, the presentation of evidence indicating that the various cycles were separated by times of uplift was deferred, but now this may be considered. The unconformities which are locally well developed, and which have been employed to separate the formations, have been described, and as these were produced by subaerial erosion it follows that the sea no longer covered this area. However, the questions might be raised whether all of these upper shales, which are commonly unfossiliferous, are actually marine, and whether in this case it might not be possible to explain the unconformities without appealing to uplift. Consequently, it is significant that locally many of these surfaces of unconformity cut

[1] C. K. Swartz, W. A. Price, and H. Bassler, "Coal Measures of Maryland," *Bulletin Geol. Soc. Amer.*, Vol. XXX (1919), p. 580.

down completely across the upper shales through the characteristically marine limestones and calcareous shales and even through the coals themselves. The limestones which certainly were deposited beneath the sea must have been upraised, or erosion of this type could not have reached them beneath their fairly thick covering of shales.

The recognition at many horizons of unconformities which are the result of uplift is of considerable importance because the widely accepted interpretation of Pennsylvanian sedimentation has been that the sea was silted up, coal plants grew upon this low surface, subsidence brought back the sea, which was again silted up, etc. Although few writers have commented upon it, the sedimentary cycle is generally so well exhibited that many must have observed it, but it has not been recognized as the result of diastrophic cycles.

DIASTROPHISM

Before concluding the consideration of cyclical Pennsylvanian sedimentation, it is necessary to consider briefly the nature of the diastrophism which controlled it. Although climatic change may have been an important factor, evidence of its influence has not been recognized and therefore it may be ignored at this time, as diastrophism alone is capable of providing an adequate explanation for the cycle.

At that stage of the cycle just before the cessation of clastic sedimentation, the extensive alluvial plain must have sloped sufficiently to allow streams to carry fine sands, that is about 6 inches or more per mile,[1] and if the plain was 1,000 miles wide its piedmont edge must have been 500 or more feet above sea-level. However, the shallow-water faunas and the variable nature of the marine sediments, including brecciated limestone, show that the subsidence which resulted in marine submergence as far east as Pennsylvania did not produce, in the Mississippi Valley, seas 500 feet or more in depth. Consequently, the uplifts and subsidences must have been of a hinge type, greatest in Appalachia and decreasing in magnitude westward. Appalachia, the area of erosion, moved dominantly up-

[1] The grade of the Mississippi River between St. Louis and Cairo is about 7 inches per mile; the fall of the Nile from Assuan to Cairo, a distance of more than 700 miles, is less than 5 inches to the mile; the Amazon over considerable stretches descends at a rate of less than 2 inches in a mile; and the Yangtse River is said to fall about 1 inch per mile in the last 200 miles of its course. Most large rivers, however, carry only fine muds in their lower course.

ward while the interior, the area of sedimentation, moved dominantly downward (Figs. 5 and 6).

In the last few years, comprehensive studies of the Carboniferous stratigraphy of the mid-continent area by geologists in the employ of numerous oil companies have produced much information concerning the geologic history of that region. These data, which recently have been summarized,[1] reveal that diastrophism was more or less active in Llanoris and adjacent areas throughout Pennsylvanian time. It is not unlikely that future studies will make it possible to correlate these movements with the diastrophism of Appalachia, which resulted in the sedimentary cycles of the northern and eastern coal fields.

INTERBASIN CORRELATION

The diastrophic movements of the Pennsylvanian period were not all of uniform degree. As a result, the areas of emergence and submergence within the cycles were not of equal extent. The strand line oscillated backward and forward unevenly, extending much farther to the east during some cycles and withdrawing a greater distance to the west at some of the intercyclical stages. Therefore, the deposits in the various seas and upon the different land surfaces were of unequal extent. However, as the transgressions of the sea after lower Pottsville time probably always came from the west and southwest, each marine invasion of Illinois should be represented in Missouri by marine beds also, but marine beds in Missouri laid down in less extensive transgressions would have no counterpart in Illinois. Likewise, after lower Pottsville time, there might have been more marine horizons deposited during a given period in Illinois than in Ohio.

In the same manner, each underclay and coal horizon in Illinois should be represented by an equivalent underclay and coal horizon in Ohio, although it is conceivable that in Ohio there might be additional ones representing land surfaces that did not extend as far west as Illinois. Similarly, each underclay and coal horizon in Missouri should have its counterpart in Illinois but not all of the Illinois horizons may have extended as far west as Missouri.

[1] S. Powers, "Age of the Folding of the Oklahoma Mountains," *Bulletin Geol. Soc. Amer.*, Vol. XXXIX (1928), pp. 1031–72; M. G. Cheney, "History of the Carboniferous Sediments of the Mid-continent Oil Field," *Bulletin Amer. Assoc. Petrol. Geol.*, Vol. XIII (1929), pp. 557–94.

During the first part of each cycle, when land conditions prevailed extensively throughout the interior of the continent, there not uncommonly occurred local accumulations of peat now transformed

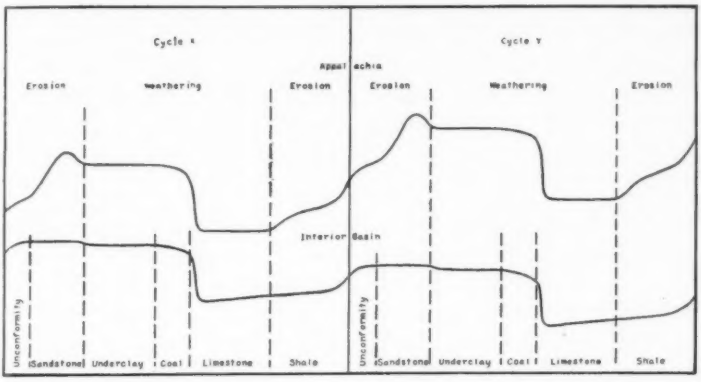

FIG. 5.—Diagram showing relative uplifts and depressions in Appalachia and the Interior Basin during the course of two typical cycles.

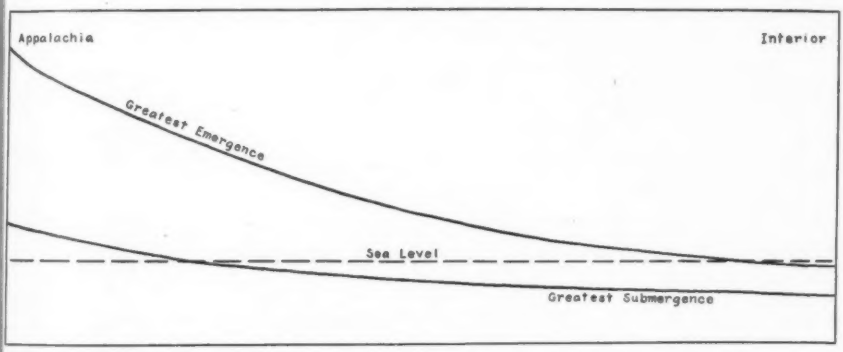

FIG. 6.—Diagram illustrating the hinge action of the Pennsylvanian diastrophism and the extremes of uplift and subsidence in Appalachia and the Interior Basin.

to thin layers or lenses of coal. Such coals are without underclays and do not represent extensive coal horizons so that they are of no significance in correlation. On the other hand, there can be no local or "stray" marine horizons, as all marine beds must have been connected with more extensive marine deposits to the west or south.

It is possible that difficulties may arise in the interpretation of the Missouri and Kansas sections because the diastrophism of Llanoris may have been imperfectly synchronized with that of Appalachia. If the uplifts and depressions of these two highland areas were not always contemporaneous but conflicted with each other, the strata in Missouri and Kansas, which may be composed of sediments derived from both of them, would be a complicated sequence of beds. However, there should be no such difficulty in the correlation of the Illinois and Ohio sections.

ESTIMATES OF TIME

Barrell has estimated that the Pennsylvanian period was from 35,000,000 to 50,000,000 years in duration.[1] If an intermediate figure of 40,000,000 be divided by two in order to make allowance for the Mississippian-Pennsylvanian unconformity and the early Pennsylvanian beds which are absent from Illinois and Ohio, the Pennsylvanian strata in these states represent about 20,000,000 years. If, for convenience, the forty-two cycles recognized in the Ohio section be increased to fifty, the time that might be assigned to an average Pennsylvanian cycle would be 400,000 years.

Each cycle includes two intervals during which deposition did not occur; namely, (1) that represented by the unconformity beneath the sandstone, and (2) that represented by the underclay. If it be assumed that deposition took place during 75 per cent of the time assigned to the average cycle, 100,000 years remain to be divided between the two intervals of nondeposition. There can be little doubt that the development of the underclay required a considerably longer time than the interval represented by the unconformity because weathering profiles have not been recognized at any of the unconformities. If the ratio of these two intervals were as 3 is to 1, an average of 75,000 years would be allowed for the development of the underclay, which might be sufficient under favorable conditions.

However, it is not at all unlikely that a considerably longer time was actually available. The faunas of the Upper Mississippian and Lower Pennsylvanian are so strikingly similar in many ways that the two periods may not have been separated by so long an interval as

[1] J. Barrell, "Rhythms and the Measurements of Geologic Time," *Bulletin Geol. Soc. Amer.*, Vol. XXVIII (1917), p. 885.

20,000,000 years. The accumulation of sediments may have required much less than 75 per cent of Pennsylvanian time. It is also highly probable that the development of an underclay actually required more than three times that represented by the unconformity. In view of these considerations, the time available for the development of an underclay might be reasonably increased to 250,000 years. Whatever assumptions may be selected, it is evident that Pennsylvanian time was amply sufficient to accommodate all of the sedimentary cycles that have been recognized, numerous though they may be.

ROCK FLOORS IN ARID AND IN HUMID CLIMATES. II

W. M. DAVIS

VALLEY FLOORS OF HUMID EROSION

The continued removal of the finer soil from the valley-side slopes causes them to recede from the banks of the graded stream to which they previously descended; and as they do so narrow strips of valley floor, shown by spaced lines in the third block of Figure 5, will be developed at their base, back of whatever flood plain, drawn with close-set lines, is simultaneously formed by the stream.[1] As these strips widen, the concavity of the profile across the valley bottom, initiated by the growth of the talus, is given broader expression, as in the fourth block.

The lateral valley-floor strips are, like the flood plain, underlaid with degraded rock, which may be called the valley-floor basement. It has a somewhat ragged and vague surface, except that where cut by lateral shifts of the stream it may be more even and better defined. The lateral strips will be everywhere covered by detritus, partly derived from local subsoil weathering, partly washed down from the valley sides; and this detrital cover will, in time, constitute a large part of the valley floor. The surface of the cover thus prepared will have the same longitudinal or downvalley slope as that of the stream and its flood plain. If the stream is of good size, its gradient will be so weak that an upstream view of the flood plain between the lateral valley-floor strips will seem nearly level. Each lateral strip of the valley floor will have, besides its downstream slope, a somewhat stronger transverse slope from the valley side toward the stream or its flood plain, so that fine soil washed down from the valley side can be transported across the strip by the agencies, rill-wash chiefly, there available for that duty.

[1] Earlier accounts of valley-floor strips of degradation have not been looked up, and I am unable to say who first called attention to them explicitly. They have been alluded to in at least two of my own writings, *Practical Exercises in Physical Geography* (1908), text, p. 41; Atlas, Pl. 8, Fig. 10; and "La vallée de l'Armançon," *Ann. de Géogr.*, XXI (1912), 312–22.

The lateral swinging of the graded stream broadens the flood plain and its rock basement, as in the front block of Figure 5, and thus the valley-floor strips may be encroached upon; but in spite of this they gain width by the retreat of the valley-side slopes. As far as the stream thus swings, it will cover the rock basement with the gravels, sands, and silts of the flood plain, which, besides having a downvalley slope, also slopes transversely away from the stream bank. In time the continued withdrawal of the valley-side slopes will carry their base farther away than the lateral swinging of the stream can reach: thereafter the valley-floor strips will be developed

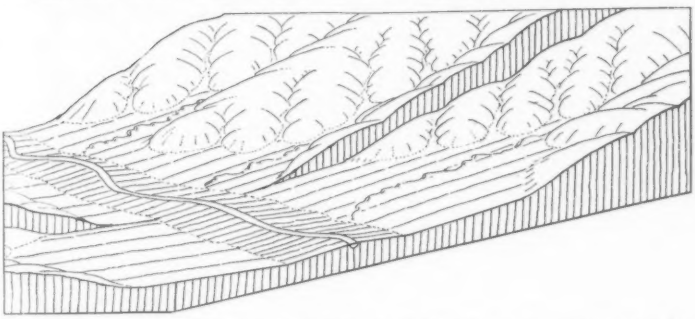

FIG. 6.—Two advanced stages of valley-floor widening with associated branch-floor development.

to greater and greater width, independent of the flood plain. In the meanwhile many brooks, short side branches of the main stream, will excavate ravines in the valley sides, as in the back block of Figure 6. The concavity of the main-valley cross-profile is then increasingly shown on the line of these brooks; it later appears part way up the valley-side spurs also; and by that time the spur crests will have become so gracefully rounded, so free from all hard-line edges, that it is difficult to make a drawing of them in which they do not look like wrinkled bolsters and pillows.

After the side-brook ravines are developed to the stage of having their own flood plains, side branches of the main valley-floor strips, each with its underlying rock basement, will be opened along their margins heading farther and farther up the ravines, as in the front block of Figure 6. The branch floors will have slightly steeper down-

brook gradients than the downvalley gradient of the main-valley strips or of the main flood plain; and somewhat steeper still will be the transverse gradient of the parts of the main valley-floor strips which lie between an interravine spur-end and the main stream or its flood plain, because there the gradient is determined only by wet-weather rill-wash instead of by a branch brook: but this delicate modulation of valley-floor slopes is not shown in the accompanying diagrams.

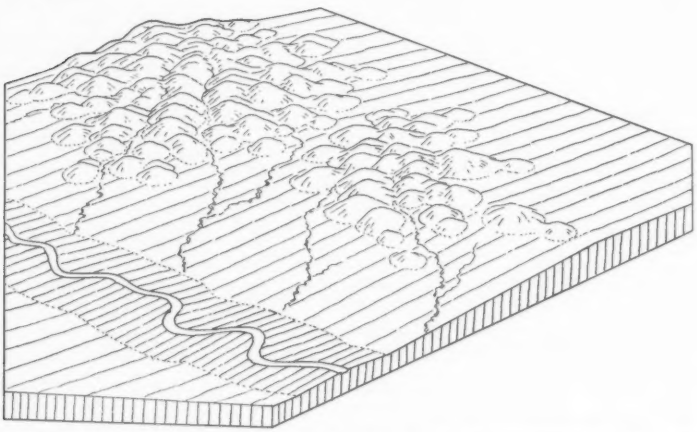

FIG. 7.—A late stage of valley-floor widening with the accompanying dissection of an intervalley ridge and the isolation of its severed parts.

Neighboring streams, subparallel to the one here figured, will develop similar ravines and valley-floor branches; the ridge crests between the ravines will be encroached upon and increasingly dissected as the ravines and their valley floors widen. Later on the ridges may be gnawed through at various points by the brookhead valley-floor branches, and successive parts of an originally continuous ridge may thus be isolated, as in Figure 7.

AGGRADATION OF HUMID VALLEY FLOORS

By this time, the load to be washed from the subdued hills of the dissected intervalley ridges across the valley-floor strips to the main streams has decreased to a less amount than when the hills were

higher and steeper; therefore, the valley floors will be worn down to gentler and gentler transverse gradients, just as they and the flood-plain belt between them are also worn down to gentler longitudinal gradients.

It may be here pointed out that several conditions associated with the development of flood plains in humid regions will cause them to increase in the three dimensions of length, breadth, and thickness, so that they come to cover an unexpectedly large part of their degraded valley floors. First, while a river is actively cutting down its valley in an uplifted highland, its channel in the valley bottom tends to remain of small width; not that lateral erosion is then inoperative, but that downward erosion is more operative. Then, as the river approaches grade, downward erosion is so much retarded that channel widening sets in actively, especially if the current is so well charged with coarse detritus that it develops a braided flow; and channel widening thus begun may continue after grade is reached. But with continued widening there must be a loss of depth, of velocity, and of carrying power; hence, in consequence of such channel widening, the fall to which the river reduced its course when grade was first reached may later prove insufficient for its work of transportation. Deposition must thereupon take place in order slightly to increase the fall, the velocity, and the carrying power; that is, some of the load must be laid down, thus steepening the river course a little and accelerating its flow so that the rest of the load may be carried. Aggradation of this kind must be zero at the river mouth and of increasing measure upstream; it may therefore be called divergent aggradation. The resulting flood plain will tend to spread laterally across the incipient valley-floor strips toward the base of the valley sides, and also headward upon the first-encountered residual riffles of the not yet graded torrential course.

Second, in consequence of this incipient aggradation, the river current, which had all been flowing in its rock-bed channel while valley deepening was in progress, will now lose some of its water to seepage in the deposited detritus; and with this loss of volume there will be still further loss of carrying power, and deposition will have to continue, again in divergent fashion. This might be a cumulative

process, were it not that the rapid gain of carrying power due to increase of velocity will soon make up for the slower loss of carrying power due to loss of volume.[1]

In the meantime a third cause of aggradation is arising. With advance of highland dissection by branch brooks, the area of wasting valley-side slopes increases and the discharge of waste from them delivers a greater and greater load of detritus for the main stream to carry. The main stream must therefore once more build up its course by divergent aggradation in order to gain velocity for its increased work. Fourth, with these various processes all conspiring to lengthen and widen the flood plain, the development of meanders is greatly favored; and the more they are developed the longer is the course of the river through the flood plain; and with greater length there must be a loss of fall, of velocity, and of carrying power, unless recourse is had for the fourth time to divergent aggradation. A fifth cause for aggradation is found in delta growth; but this cause produces only parallel aggradation, and is therefore less effective (except close to the river mouth) in producing an increase in depth of flood plain than are the four causes of divergent aggradation.

It is not intended to assert that all these causes of aggradation operate, as here outlined, during the pre-mature stages of all rivers in all humid regions; but it seems probable that, if they operate at all, they will conspire to extend flood-plain deposits beyond the limits that would otherwise be reached. If so, the flood plain will increasingly overlap the side-strips of normally degraded valley floors: but, even then, an upstream view along the flood plain of a fair-sized or large river will seem almost level. Furthermore, after reaching a maximum of aggradation in the maturity of a normal cycle, when the discharge of waste from the valley sides is believed to reach its greatest measure, a graded river will have a decreasing

[1] It may be noted in passing that, while the power of running water to carry detritus theoretically increases with the sixth power of the velocity, the carrying power of an actual stream will not increase faster than the fifth power of its velocity, because its cross-section will diminish as much as its velocity increases. That is, if a given stream runs twice as fast as before, it will be only half as large, and it will therefore have only half as many threads of current available for the work of transportation. On the other hand, inasmuch as a stream in flood increases in size as well as in velocity, its carrying power will be increased by more than the sixth power of its velocity.

load, because of decrease of valley-side height and slant; the river will then resume its degradational work and will slowly wear away the flood-plain deposits; yet in so doing it will not terrace them because their surface will be worn down *pari passu* with the slow wearing down of the entire valley floor. The river will thus in its later maturity sweep away all the earlier-formed flood plain and return to the long-postponed task of slowly wearing down the rock basement of its first graded course, and will gradually reduce it to the fainter and fainter gradients of old age. In the meantime the previously formed and temporarily buried lateral strips of valley floor will be laid bare and will gain increased breadth by the recession of valley-side spur ends.

DISSECTION AND DEGRADATION OF A MOUNTAIN MASS

In consequence of retrogressive erosion by the headwaters of various streams and branch brooks which gain steeper gradients and increased activity of erosion as the torrential intermediate course of a river is deepened, an uparched highland will be more and more dissected through advancing and passing maturity, until its central part comes to be resolved into several more or less completely separated mountains, while its interstream spurs will be, as already noted, divided and subdivided, especially in their terminal parts, by branching ravines into isolated groups of mounts or hills. All the chief valley floors and their rock basements, reduced to gentle or faint downstream gradients, will be growing wider and wider at the expense of the spurs, ridges, and mountains; and the soil-cloaked, tree-covered slopes of the mountains, mounts, and hills will be worn down to gentler and gentler declivities, because the downwash of soil from their convex upper slopes will be faster than its removal from the base of the slopes, where it will coalesce with the soil cover of the widening valley floor in a smooth concave curve.

Soil-creep, although acting with increasing slowness as relief weakens, appears to be of growing importance at this advanced stage of the cycle in comparison with stream corrasion and rill-wash; for it is largely by soil-creep that the sharper crests of early-mature mounts, ridges, and spurs are rounded off and subdued to low mounds of gently convex cross-profile in late maturity and early old age.

PENEPLANATION

As old age comes on, the mounts and hills, already well subdivided and subdued, are reduced in area and are worn down to so moderate a relief that no sharp line of demarcation can be drawn between their slopes and the margin of the ever widening and slowly lowering valley floors; but a zone of transition may be recognized where the convex profiles of the residual hills gradually become concave as they are continued down to the broad valley floors, which slant very faintly toward their streams. By this time the rainfall, increased at the time of original upheaval, has lessened in consequence of loss of mountain altitude; and the discharge of rainfall in rills is also decreasing, not alone because of diminishing supply but also because a greater share of the rain that falls soaks into the ground, now that the slopes are weaker and the soils are deeper. Hence the direct run-off is decreased and a larger proportion of the rainfall is delivered to the streams as ground-water emerging in channel-side springs. The brooks and rivulets may therefore lose some of the headwater length that they enjoyed earlier, when slopes were steeper; and with this loss the widely opened ravine heads may be somewhat obscured by soil-creep. It is also in this later stage of the cycle of erosion that chemical weathering is believed to play the largest part in maturing the almost stationary soil cover, even to the point of decomposing feldspars, extracting their silica, and leaving the residue as hydrated alumina or bauxite.[1]

The peneplanation of a humid region, thus approached during a late stage of an undisturbed cycle of humid erosion, will be very slowly attained, because all the streams, then receiving a diminishing load of finer and finer detritus, will assume fainter and fainter gradients and wear down their courses deeper and deeper into the land mass; and therefore the valley floors and the inter-stream hills must also be worn down lower. That is, the widespread degradational processes working on the inter-stream hills must continually strive to reduce them to grade with the slowly degrading valleys; but all the changes thus brought about are accomplished at a slower and slower rate. The degradational processes are truly attaining a greater and greater measure of success in their endeavor as time

[1] C. K. Leith and D. W. Mead, *Metamorphic Geology* (New York, 1915).

flows on, but a small difference of altitude must long remain between broad hill arches and broad valley floors, even though it is a diminishing difference. The main divides between the larger, opposing rivers of the region will be reduced to low and broadly convex swells, delicately diversified by wide-open and shallow valley heads of branching streams. Minor divides will be of similar but less pronounced form. If a peneplain, thus worn down, extends a thousand miles from its ocean border into a continental interior, its old rivers with a fall of 1 or 2 feet to a mile will not reduce its interior parts below an altitude of 1,000 or 2,000 feet; hence while a peneplain is a surface of low relief, it is not necessarily a lowland over all its extent.

It is today extremely rare to find even a peneplain, much less a plain of degradation, in a humid region still holding the attitude with respect to baselevel in which it was degraded; but if any such peneplains were found, we may be sure that they would everywhere have rock basements underlying their well-developed soil cover. Yet uplifted and more or less dissected peneplains are of relatively common occurrence; and this seems to mean that, before their uplift, a longer period of crustal quiescence had elapsed than has elapsed since the initiation of the various cycles of humid erosion now current in the better-known parts of the world.[1]

ACTUAL VALLEY FLOORS

We are here, however, less concerned with a study of undisturbed peneplains than with a comparison between pediments of arid erosion in Arizona and valley floors of humid erosion elsewhere. No examples of well-opened valley floors in humid, fault-block mountains of granite are known to me; but a number of humid valley floors otherwise conditioned may be instanced, which certify to the correctness of the inference outlined above that open valley floors underlaid with rock basements would be in time excavated in granitic fault-block mountains, if such mountains were anywhere provided in a humid region. One long and broad, soil-covered valley lowland, containing many flats separated by low residual ridges and unquestionably underlaid by a worn-down rock basement, follows the belt of weak and gently inclined Triassic sandstones and shales

[1] W. M. Davis, "The Peneplain," *Amer. Geol.*, Vol. XXIII (1899), pp. 207–39.

which traverses England from the northeast coast near Newcastle-on-Tyne to the southern coast near Exeter; but as much of this lowland has been somewhat modified by glaciation, it cannot serve us here as a pure type. A smaller English example, also diversified by residual ridges but without glacial complications, follows various weak formations between the cuestas of the Oolite and the Chalk from Oxford to Cambridge; a third embraces the lowland within the oval circuit of the North and South Downs south of the lower Thames. Several wholly normal examples of fairly broad valley floors are found between the cuestas of northeastern France, the broadest being the Champagne, east of Paris and between Rheims and Châlons-sur-Marne. All of these broad and well-degraded valley floors must have rock basements at a small depth below their soil-covered lowland surface.

The humid eastern part of the United States contains no extensive, non-dissected valley floors today, but it possesses many that, after fairly broad development in a former cycle of erosion, are now suffering submature dissection in consequence of a relatively recent uplift of their region. Such are found in abundance along the belts of less resistant strata in the folded Appalachians from Pennsylvania and Virginia to Tennessee and Alabama: the advanced stage of degradation formerly reached by some of these valley floors is attested not only by the evenness of their uplands above the incised valleys of the present stream courses, but also by the occurrence there of bauxite, resulting from penultimate or ultimate decomposition of the surviving soils on the uplands while they were valley floors.[1] Still more extensive valley floors must have been produced in the Appalachians at the close of an earlier cycle of erosion, in which even the resistant strata, the ridge-makers of today, were worn down to low relief, as testified by their now nearly level crests of fairly accordant height; for at that time the weaker strata between the resistant ones must have been reduced to true plains of degradation.[2] Similarly, the uplands of the Piedmont belt in Virginia and the Carolinas must have, before uplift and mature dissection, con-

[1] G. I. Adams, "Bauxite Deposits of the Southern States," *Econ. Geol.*, Vol. XXII (1927), pp. 615–20.

[2] Bailey Willis, "The Northern Appalachians," *Nat. Geog. Monogr.*, Vol. I (1895), pp. 169–202.

sisted largely of the broad and faintly separated valley floors of many Atlantic rivers,[1] the heads of the valley-floor streams having been retrogressively excavated in the southeastern flanks of the Blue Ridge, where they occasionally captured a high-perched stream of the loftier northwestern slope.[2] Excellent views of the flat piedmont surface below the steep slope of the Blue Ridge are given by Wright, who notes that, at various points, "the Piedmont [upland] juts right into the base of the [Blue Ridge] escarpment."[3] The truncated crystalline rocks in the basements of all these piedmont valley floors were then and are still, in spite of their submature dissection today, well hidden under a heavy soil cover.

COMPARISON OF HUMID AND ARID REGIONS

The erosional processes and the forms of humid and of arid regions may now be compared. Certain of the forms, such as branching valley systems which subdivide mountain masses, are manifestly common to both. Certain others are usually thought to be unlike. Conspicuous among these are, on the one hand, the soil-cloaked and forested slopes of maturely dissected mountains in a humid region together with the fertile valley floors below them, and on the other hand the rocky and boulder-clad slopes of maturely dissected mountains in arid regions together with the barren pediments below them. These contrasted features have, indeed, been regarded by some physiographers as so completely unlike as to indicate that the erosional processes of humid regions must be correspondingly unlike those of arid regions.

The comparison here to be instituted will show that, while various contrasted features are truly enough unlike in certain respects, their unlikeness is rather a matter of degree than of kind. The apparently unlike features are really homologous; their resemblances, once recognized, are much more striking than their differences. The same may be said of the erosional and degradational processes by which the apparently unlike forms are sculptured

[1] Arthur Keith, "Geology of the Catoctin Belt," *U.S. Geol. Survey Fourteenth Ann. Rept.*, Pt. II (1894), pp. 285–395.

[2] W. M. Davis, "The Stream Contest along the Blue Ridge," *Bull. Geog. Soc. Phila.*, Vol. III (1903), pp. 213–44.

[3] F. J. Wright, "The Erosional History of the Blue Ridge," *Denison Univ. Bull.*, Vol. XXIII (1928), pp. 321–44. See p. 329 and Pls. lxxvii and lxxviii.

CONTRASTS OF HUMID AND ARID PROCESSES

In both humid and arid regions the processes of weathering are partly physical, partly chemical; more physical than chemical in arid regions, more chemical than physical in humid regions. But let it be noted that, wherever bare-rock surfaces are exposed in humid regions, there surface weathering is largely physical; and, conversely, that wherever detrital deposits containing ground water lie on bed rock in an arid region the subsurface weathering may be largely chemical. In other words, in both regions weathering will vary according to its physiographic opportunity; and this opportunity will vary from place to place at any one stage, and at the same place in successive stages of a cycle of erosion.

In both humid and arid climates, rill-wash and soil-creep are operative, but soil-creep appears to be favored and rill-wash hindered on the heavily soil-cloaked and forested slopes of maturely dissected mountains in humid regions, while rill-wash is favored and soil-creep is weakened in the thin, stony soil on the rocky and barren slopes of maturely dissected mountains in arid regions. In both, the water courses divide and subdivide repeatedly, but their subdivision is carried much farther in arid regions where every rivulet has its little valley than in humid regions where plant growth greatly impedes the formation of rivulets. This contrast is especially striking in the later stages of humid and arid cycles of erosion: for then, as noted in the foregoing, the headwater stream lines are more or less obliterated by the smoothing actions of rill-wash and soil-creep on low, plant-covered forms in the old age of a humid cycle; but they are still abundant and manifest on the worn-down, barren rock floors of a well-advanced arid cycle. In both, the streams vary from time to time in volume of discharge, but the variations are vastly greater in arid than in humid regions; for in humid regions streams seldom fail to flow, except at their very heads during droughts; while in arid regions streams seldom flow anywhere except locally, at one or another part of their courses, for a short time during and after rains. A housekeeper from a humid region once exclaimed, on seeing clouds of dust blown from the dry channel of a river in an arid region, "I never before saw a river whose bed was so well aired!" and it

could have been only in a humid region that a poet would write of a brook, "I go on forever."

In both humid and arid regions, streams in time reduce their courses to grade; but, other factors being equal, the graded streams of an arid region, heavily charged with relatively coarse detritus, have a steeper fall than streams of the same size in a humid region, where by reason of the presence of a plant cover the detritus given to the streams to carry is moderate in quantity and fine in texture. Here, again, the arid-humid contrast is most striking in the later stages of the cycle of erosion; for while the aging streams of a humid climate will, because of the small quantity and fine texture of their detrital load, have reduced the peneplain that they drain to a nearly level surface of almost imperceptible slope along the stream lines, the aging streams of an arid climate may still have, by reason of their relatively abundant and coarse load, very perceptible slopes on their barren rock floor.

RESEMBLANCES OF ARID AND HUMID MOUNTAIN SLOPES

As the various processes of arid and of humid erosion are thus seen to differ in degree and manner of development rather than in nature, and as their differences in degree and manner are wholly due to differences in their climates, so the forms produced by the two erosions may be shown to differ in the degree to which certain elements of form are developed rather than in the essential nature of the elements themselves.

For example, the maturely graded slope of a soil-cloaked and forested, granitic mountain in a humid region is really about as well boulder-clad as a maturely graded and barren granitic mountain slope is in an arid region. The difference between the two is that the boulders on the humid mountain slope are hidden under a soil cloak and the soil cloak is hidden under a forest cover, while the boulders on an arid mountain slope are, in the almost complete absence of finer soil and of plants, clearly visible. In both cases, after the graded slope is developed, the weathered boulders rest upon more or less decomposed bed rock. In humid regions, and especially in warm humid regions, the underlying bed rock may be, if of granitic nature, decomposed in mass to depths of 30, 50, or more feet below the subsurface boulders; in arid regions rock decomposition penetrates to a

much less depth. In both cases, the boulders on graded slopes do not roll down to form a heavy talus at the mountain base, but are for the most part destroyed by disintegration while they are resting on or slowly descending the slope.

On graded humid slopes, by the time that the finer surface soil is removed by wash and creep, as if to reveal the underlying boulders of subsoil weathering, the boulders themselves are reduced to soil and new boulders are formed by deeper weathering of the bed rock behind them. As to the boulders on graded arid mountain sides, Bryan's account of the Papago country in Arizona tells us:

> Under conditions normal to the region few boulders reach the bottom of the [mountain] slope. . . . . Great heaps of boulders do not occur at the mountain base. Fine débris forms a loose film over the surface between the boulders. . . . . The bedrock on which the boulders lie is . . . . as thoroughly disintegrated as the interior of the boulders. . . . . Every rain sets in motion down the slope trains of this fine débris. As the slope steepens locally by the removal of the fine débris, the boulders roll down to find new lodgment lower on the slope or at the base. In this movement many boulders already disintegrated within the outer crust are shattered to fragments. . . . . As the bedrock of the mountain slope disintegrates, and the rain washes away the fine fragments, protuberances of the bedrock are left that consist of the most compact rock between the most widely spaced joints. The protuberances are cut loose from the bedrock by the same processes that formed them, and a new crop of boulders comes into existence [pp. 85–86].

Clearly the contrast between the visibility of boulder-clad rock slopes in arid mountains and their invisibility in humid mountains is wholly due to the difference of their climates; and as clearly the visibly boulder-clad rock slopes of arid mountains are closely homologous with the invisibly boulder-clad rock slopes of humid mountains.

DIFFERENCES BETWEEN HUMID AND ARID MOUNTAIN SLOPES

A striking difference between humid and arid (granitic) mountains is found in the decreasing angle of slope of the first as the erosion cycle advances, in contrast to the constant angle of slope in the second; but this, like the invisibility and visibility of boulders on the slopes, is again wholly a consequence of a difference of processes due to a difference of climate. In a humid climate the steep and partly bare walls of a young valley, with scanty and coarse detritus lodged on its ledges, are succeeded by the less steep side-

slopes of a mature valley, cloaked with abundant soil and overgrown with forest, the gentler declivity of the slopes being appropriate to the weaker processes of soil removal then in operation. As maturity is slowly followed by old age, the soil cloak is weathered to greater depth and to greater fineness at the surface, and the valley-side slopes are reduced by wash and creep to gentler declivity still.

In an arid climate the young stage of valley erosion, producing steep and bare rock walls if the streams are vigorous enough to erode such valleys, is soon followed by the mature stage of boulder-clad slopes if the rock weathers to boulders; but thereafter the declivity of the slopes remains unchanged, because in consequence of aridity they do not become soil-cloaked and plant-covered but remain persistently barren and boulder-clad until the widening of the valleys consumes them. As Bryan puts it, "By these slow but continuous processes [of weathering and washing on graded granitic slopes] the mountain front recedes, maintaining its angle of slope according to the spacing of joints and the granular structure of the granite" (p. 86). As the mountain mass is increasingly dissected and subdivided into island-like hills, "each of these hills retains the slopes characteristic of the rock and gradually decreases in size. . . . . Solitary . . . . hills retain the same steep slopes as the original mountains, but grow gradually smaller until the last remnants are masses of boulders or single rocks projecting above the general level" of a pediment (p. 96). Evidently, constancy of slope in this case and decrease of slope in the other are wholly determined by differences of climate.

Associated with the contrast between the persistence of a uniform slope in wasting arid mountains and the systematic decrease of slope in wasting humid mountains is the contrast between the abrupt, almost angular change from the slope to the piedmont pediment in (granitic) arid mountains and the curved change from slope to valley floor in humid mountains. But even in a humid mountain, the change from slope to valley floor is abrupt in an early stage of their erosion, when the valley sides are steep and the valley floors are narrow, because there is then a rather abrupt change from the coarse detritus of the slope to the finer detritus of the floor; it is only as time passes and the slope is decreased and its detritus is refined that the slope blends into the floor by a more or less curved descent.

RESIDUAL MOUNDS ON PENEPLAINS AND ISLAND-MOUNTS ON PEDIMENTS

Although the residual mounds on humid peneplains and the island-mounts on arid pediments are strictly homologous, it is a mistake to treat them as essentially identical, as some German writers seem inclined to do. The first are pale forms of weakening convexity and lessening slopes which merge, without any sharp line of demarcation, into the surrounding lower surface, and which gradually fade away as time passes. The second are of vigorous form and are, especially in granitic areas, sharply separated from the surrounding rock floor; they retain their vigor, in spite of losing size, even to the moment of their extinction. It is therefore inappropriate, to say the least, to confuse the fading mounds on humid peneplains with vigorous island-mounts on arid pediments; for, according to Bornhardt's original definition of Inselberge, they are steep and rocky mounts which rise boldly from the surrounding rock floors like islands from the sea.

To be sure, if a humid peneplain is worn down beneath a land area on which volcanic action had previously taken place, its faintly undulating surface would be here and there sharply interrupted by dikes and stocks; but these special structures have little in common with the pale residual mounds on peneplains of uniform rock structure. It is, indeed, entirely unnecessary to assume that the fading mounds of humid peneplains or the bold island-mounts of arid pediments consist of more resistant rock than that which is smoothly worn down in the surrounding lower surface, as von Stapf seems inclined to do. And there is no more mystery in the survival of bold island-mounts over a widening rock floor than in the surviving of pale residual mounds over a humid peneplain; for inasmuch as the production of arid rock floors is, like that of humid peneplains, a slowly progressive and not an instantaneous process, the survival of residuals here and there at a late stage of the process before the ultimate stage is reached, is in both cases inevitable. The process begins with the incision of narrow valleys in irregularly branching arrangement; it goes on with the widening of the valley floors, in consequence of which the intervalley highlands are progressively and irregularly consumed. It is out of the question that all parts of such

irregularly bounded highlands should be simultaneously destroyed; the survival of residuals here and there is an inherent element in their reduction to rock floors.

The two kinds of forms, island-mounts and residual mounds, stand at the opposite ends of an arid-humid series, which must include many intermediate forms; and although the successive members of such a series must grade into each other, the members at the opposite ends of the series are as unlike as early youth and advanced old age are at the opposite ends of the series of life-changes; as unlike as torrid and frigid climates are at the extremes of a series of intermediate climates.

HOMOLOGY OF HUMID VALLEY-FLOOR BASEMENTS AND ARID MOUNTAIN PEDIMENTS

Visibly sloping, piedmont pediments of bare rock, thinly veneered with cover-patches of rock chips and sand, are the most peculiar features of erosion in an arid climate; and they are commonly regarded as altogether different from anything that is to be found in a humid climate. Yet the faintly sloping bed-rock basements of valley floors in a humid climate, invisible because covered with slow-creeping soil and flood-plain deposits, are truly counterparts of the more strongly sloping, bare-rock pediments in an arid climate; just as truly as the invisibly boulder-clad slopes of humid mountains are counterparts of the visibly boulder-clad slopes of arid mountains. Both valley-floor basements and piedmont pediments grow most rapidly along the larger streams of their districts. Such is clearly the case in humid regions, and the same is true, according to Bryan, in arid regions:

> The pediment grows most rapidly along the major streams. In every indentation in the mountain front and in places where streams emerge from the canyons onto the plains the rate of formation of the pediment is rapid, and consequently extensions of the pediment into the mountains are common. These extensions consist of branching valleys, many of which are two miles or more in width and reach far into the interior of the mountain mass [p. 97].

Both humid valley-floor basements and arid pediments are developed by the lateral extension of valley bottoms at the expense of the inclosing slopes; the extension of both is aided by the swinging of their streams, as is well known to be the case in humid regions

and as Bryan certifies for his arid region. He states explicitly that mountain-slope recession and the associated widening of the piedmont pediment are "aided by the erosive action of streams in lateral migration" (p. 89). "The pediment is greatly increased in extent by lateral migration of the streams at and below the mouths of canyons. The irregularities of the pediment are removed, the higher places being eroded and the lower filled with débris and protected" (p. 96).

Apart from the concealment of one and the visibility of the other, the chief difference between these two homologous features is the manifest ascending slope of the arid pediment in its extension upward from its alluvial embankment, and the almost imperceptible ascending slope of a humid valley floor from its terminal delta. In consequence of this, the residual mountains that rise from the center of a well-developed pediment seem to have a high-perched base that is reached by a long and smooth, rock-floor ascent from the surrounding aggraded basin-plain, while the residual mountains at the head of maturely widened, humid valley floors do not appear to have a high-perched setting.

SUBDIVISION OF HUMID AND OF ARID MOUNTAINS

Earlier paragraphs have described the manner in which humid erosion accomplishes the resolution of a single, uparched fault block into a maturely dissected mountain group, with isolated and subdued outliers between the widened floors of the outgoing valleys. A very similar subdivision of arid mountains takes place, but by reason of the persistent abruptness of their slopes, the isolated outliers and monticules stand forth more conspicuously than do the subdued moundlike outliers of humid (granitic) mountains. Yet the essential similarity of the two cases becomes manifest when it is recognized that the subdivision of an originally single mass into its maturely separated parts is wholly the result of the deepening and widening of stream-eroded valleys, as they branch this way and that, extending their length by headward erosion in the most ordinary manner, and thus cutting the peripheral parts from the central mass.

Bryan gives various details of those progressive changes:

> After the stage of maturity is reached . . . . slope recession and the lateral cutting of the streams are the dominant processes. . . . . The residual masses [between opposing streams] are reduced to isolated island-like hills. . . . . Each

of these hills retains the slopes characteristic of the rock and gradually decreases in size through slope recession assisted by the erosive action of streams in lateral migration over the plain. . . . . The residual hills are strung out in lines between the original canyons [p. 89]. . . . . When the [intervalley] spurs become narrow they are cut through by slope recession on both sides, and hills are left standing as outliers on the pediment. These solitary hills are worn away with extreme slowness. . . . . The hills retain the same steep slopes as the original mountains [p. 96]. . . . . The normal pediment has a smoothly sloping surface . . . . broken only by scattered hills which rise abruptly from its surface . . . . many of which are prolongations of the intercanyon ridges of the mountains [p. 94]. . . . . The extension of the pediment may thus divide the original mountains into groups of detached hills separated by relatively broad surfaces cut on rock [p. 97].

THE SLOPES OF HUMID VALLEY-FLOORS AND OF ARID PEDIMENTS

In no respect are humid valley-floors and arid pediments more homologous than, as already noted, in the relation of their gradients to the transportation agencies working upon them. The gradients of humid valley-floors are of low value because their streams are supplied with water in abundance and with rock waste in moderation. The gradients of arid pediments are of high value because, although their water supply is occasionally abundant, the rock waste to be carried is great in quantity and coarse in texture. The variation of gradients on different parts of a humid valley floor have already been detailed; they are gentlest along the course of the flood plain of the largest streams, a little steeper along the flood plains of the minor streams, and steepest on the transverse slopes of the valley-floor strips from spur ends to flood-plain border. Precisely similar variations are found on arid pediments.

As Bryan states, the transportation agencies "cannot operate below a level determined by the grade necessary to transport detritus away from the mountains" (pp. 96–97). The slope of a pediment away from a mountain base is such that "débris is swept outward . . . . by small rills which originate through the concentration of rain wash at the base of the mountain slope." The rills "operate only during or immediately after a rain" (p. 96).

Transportation of relatively fine material by water is the essential factor in the formation of the pediment [p. 97]. . . . . In any one mountain range the slope of the pediment is steeper opposite the smaller canyons and very much flatter opposite the larger canyons. The parts opposite the inter-canyon portions of the mountain front are steeper than the parts opposite the canyons [p. 95]. . . . .

> The grade of the rills and of the smaller streams is steeper than that of the larger streams. . . . . As a result of this relation of stream grades, the pediment, cut and molded by these streams, has a lower slope opposite the larger canyons than opposite the smaller canyons. Also, the parts of the pediment opposite the inter-canyon spur ends have a steeper slope away from the mountains

than the parts that lie along the stream courses (p. 96).

WEATHERING OF HUMID BASEMENTS AND OF ARID PEDIMENTS

The bed-rock basements of valley floors in humid regions and the piedmont pediments in arid regions are more or less completely covered with detritus that is intermittently on its way downstream. The detritus in humid flood plains is so deep and continuous that the underlying basement is seldom thought of. The same is true for the basement under the lateral strips of the valley floor, beyond the reach of the flood plain: they are always soil-covered, and the cover, although in slow progress toward the stream, is so persistently present that the basement is never naturally exposed. Moreover, all across a humid valley floor the water table lies near the surface and the surface is abundantly plant covered; there is nothing in sight to suggest that the concealed valley-floor basement is the homologue of the visible arid pediment; yet such it truly is.

In contrast with the soil-covered basement of humid valley floors, the rock pediments in arid regions are usually discontinuously covered with a thin veneer of detritus: yet the intervening and sometimes smaller areas of completely bare rock may more strongly impress the observer, especially if he comes from a humid region, by their strangeness, and he may thus be led to overlook the close resemblance of the visible arid pediment of the unfamiliar desert to the hidden rock basement of the humid valley floors with which he ought to be familiar.

Humid valley-floor basements as well as arid pediments are ordinarily weathered more or less below the detritus that covers them. This is manifest enough in arid pediments, where the exposed rock surface is very generally split, chipped, and crumbling. It is much less manifest in humid, valley-floor basements, because the bed rock there is so universally buried. But when the rock is reached in excavations, it is found to be more or less decomposed, especially under the valley-floor side-strips. Beneath a flood plain, firmer bed-

rock may be found where the stream has lately scoured the basement at time of flood.

FLOOD SCOURING OF BASEMENTS

Flood-scouring of basement bed rock beneath a flood plain may take place even when no rock in place is to be seen in the river bed at low water. Observations made on the Colorado River at Yuma under the United States Bureau of Reclamation show that at low water in September, 1921, the river surface stood at 113 feet, gage-height, with a breadth, partly occupied by a 200-foot sand bar, of 480 feet, and a maximum depth of from 6 to 8 feet in a mid-channel about 100 feet wide; the total discharge was then 1,200 cubic feet a second. These figures appeared to be typical of previous low-water seasons. During a flood in the previous June, the water surface rose to 131 feet, gage-height, with a breadth of 570 feet, a general depth of 60 feet, and a maximum depth of 66 feet in a channel about 300 feet wide; the total discharge then being 186,000 cubic feet a second, or 155 times the low-water discharge. The significant item here in connection with the scour of buried valley-floor basements is that, while the flood surface rose 18 feet, the flood bed deepened 41 feet, or nearly two and a half times the rise.

It may be pointed out that the deepening of a river channel during a flood involves the lifting of a large volume of detritus into the flood current, and that while thus lifted, the detritus is shifted downstream over a considerable distance before it is laid down again as the flood subsides. The flood-water lift and shift of detritus thus accomplished down the slope of a valley-floor basement in a humid region corresponds closely with the sheet-flood lift and shift of débris down the slope of a rock pediment in an arid region.

SIMILARITY OF HUMID FLOOD PLAINS AND ARID ALLUVIAL EMBANKMENTS

The aggradation of a flood plain, with its resulting extension farther and farther upstream on the rock basement of a degrading valley floor in the earlier stages of a cycle of humid erosion, as described in the foregoing, shows a certain similarity to, although hardly a homology with, the upbuilding of an alluvial embankment, with its headward extension over the suballuvial rock bench or pediment

which widens as it is worn down, as explained by Lawson. The similarity is chiefly between the parallel aggradation of the flood plain, due to forward delta growth by reason of the early downwash of abundant detritus by active young rivers, on the one hand, and the parallel aggradation of the alluvial embankment, due to upward filling of its distal intermont basin by reason of the early inwash of abundant detritus by active young stream-floods, on the other hand.

Again, the past-mature degradation of an aggraded flood plain, caused, first, by reason of the lessened load coming from the subdued slopes of its headwater hills, and, second, by reason of the retrograding abrasion of its delta front, may be compared with the past-mature degradation of an arid alluvial embankment, caused, first, by reason of the lessened load coming from the lowered island-mounts at its head, and, second, by reason of the lowering of its intermont basin by wind exportation of dust; for such exportation becomes effective when an arid region is worn down and filled up to low relief in the later stages of its history, and when the detritus supplied to the basin is therefore smaller in quantity and finer in texture than in the earlier stages.

Finally, a true homology may be drawn between the slow degradation of a humid and soil-covered peneplain of hardly perceptible declivity after all its mountains and mounts are laid low and the slow degradation of an arid and thinly veneered pediment of very visible declivity after its retrogressive extension has consumed all its surmounting peaks and pinnacles. But these somewhat transcendental considerations need not be pursued farther for the present.

ADDITIONAL COMPARISONS BETWEEN HUMID AND ARID EROSION

All the physiographic differences outlined in the foregoing between the processes and forms of humid and of arid erosion are clearly the direct or the indirect consequences of differences of climate. The comparisons on the preceding pages have been limited to fault-block mountains of massive granitic rocks in humid and in arid climates, but this is because only granitic rocks occur in mountain-sized masses of essentially uniform structure. While actual examples of such mountains are, it is thought, known in Arizona, no examples of similar mountains are here adduced in a humid climate. The reader

may determine how far the preceding comparisons are thereby vitiated.

It is true, furthermore, that many mountains in both humid and arid climates do not consist of granite; they will therefore be more or less unlike those described. For example, mountains of slate would have a thin, shingly soil, their slopes would be of moderate declivity even in the desert, and their base would curve gradually into their pediment. Bryan has made clear the principle here involved (pp. 80–81). Again, mountains composed of alternating belts of resistant and weak rocks will be degraded unequally in their resistant and weak parts; they will not be worn down in simple forms, but will favor the development of subsequent valleys along the weak belts and of subsequent ridges along the resistant belts. No mention of these special forms was made in the foregoing, because their pediments will be diversely developed. If space permitted, some account of such mountains might be undertaken, but there is not sufficient need of thus extending the present discussion. The principle in question is, in my opinion, satisfactorily established without it, not merely by the general statement that residual mounts may be produced by advanced erosion in any climate, but by a critical comparison of the forms produced in unlike climates with due regard to their differences as well as to their likenesses. In view of that comparison as presented in the foregoing, it seems to me perfectly legitimate to treat the cycle of arid erosion as a climatic modification of the cycle of humid erosion; but it is, at the same time, highly desirable, indeed essential, to recognize and to emphasize the contrasted processes and products by which the two cycles are so strikingly characterized.

Various other problems remain for fuller discussion. One of these is the occasional occurrence of well-rounded, soil-covered mounts between maturely developed valleys of normal appearance in arid regions: for example, in the basement crystalline rocks on the frontal slope of the Galiuro mountains in southeastern Arizona.[1] Another is the occurrence of low and fading residual mounds of very gentle slope, quite unlike the typical steep-faced island mounts of arid

[1] W. M. Davis and Baylor Brooks, "The Galiuro Mountains," *Amer. Jour. Sci.*, Vol. XIX (1930), pp. 89–115.

regions, yet such as are occasionally seen in the dry country of western Utah. A third is the origin of the rounded summits of granitic domes—Lawson's "panfans"—in southeastern California, which appear to violate the "law of divides" as formulated by Gilbert. A fourth is a detailed study of the African rock floors, in order to determine whether they still, in spite of their advanced stage of development, exhibit the variations of slope deduced by Lawson and described by Bryan; and also to discover whether they are still undergoing slow degradation, as suggested in the foregoing.

A fifth, and to me a very baffling, problem is concerned with the relative rates of erosion and degradation in humid and in arid regions. It seems as if humid stream erosion must—other things being equal—be more rapid than arid stream erosion in the early stages of an erosional cycle; also that, in a much later stage, degradation may be more rapid on the bare slopes of an arid region than on the plant-covered slopes of a humid region. It may even happen that an inclined but smooth rock-floor plain of degradation is sooner prepared under an arid climate than a nearly level, soil- and plant-covered plain of correspondingly faint relief can be produced under a humid climate; the reason for this being found in the persistence with which the steady-flowing humid rivers continue to degrade their courses and their valley floors to fainter and fainter gradients until they are very nearly level, thus leaving the fading intervalley hills always in relief, while the intermittent rivers of arid climates seem content to permit the slanting planation of their basins while their gradients are still rather strong; but no definite pronouncement on these problematic matters is here intended. Evidently enough, abundant physiographic problems await the observer who has opportunity for research in arid regions.

THE SIGNIFICANCE OF THE WORD "EUTECTIC"

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ABSTRACT

Attention is called to the fact that "eutectic" has been used in varying ways, and that some confusion has resulted; also that analogies have been drawn between the final stages of crystallization of natural magmas and those of laboratory melts, from which, in some instances, they differ in essential particulars. Careful consideration of the word's meaning and implications is urged.

It is often of great importance in scientific writing that all who use a term should have the same understanding of its meaning.

A recent contribution published (in English) by the Geological Commission of Finland, entitled "Eutectics and the Crystallization of Igneous Rocks," by Walter Wahl (Helsingfors, 1929), has served to call attention to this fact. In this pamphlet the author differs somewhat from conclusions previously stated by Bowen as to the importance of eutectics in igneous rocks, and at another place a mild criticism of certain views of mine is given. On reading the article carefully it is found that the divergence of views is due in large measure to the fact that to Wahl "eutectic" means something different from what it does to Bowen or to me.

The early pages of Wahl's article are devoted to "the theory of eutectics," and the later pages to "igneous rocks considered as eutectic systems." Under the theoretical part, some of the familiar standard methods of representation of phase rule diagrams of cooling systems are shown and explained, and later an application to igneous rocks is made. In both parts of the article the terms "eutectic lines" and "eutectic surfaces" are frequently used, especially in connection with systems containing mixcrystals, to the discussion of which a large part of the article is devoted.

Until Wahl's paper directed special attention to the matter, I had regarded the word "eutectic" as applicable with strict propriety only to a *point* on a phase diagram, and I have used it in that manner. In fact, I believe that has been the general usage in papers of the Geophysical Laboratory. The lines and surfaces related to the

eutectic point have been called "boundary lines" and "boundary surfaces."[1]

Wahl's point of view in the use of "eutectic" may be illustrated by the following quotation (p. 12):

> Now these views are at least to a certain extent dependent on the manner in which we define the term "eutectic," whether we limit it—as Bowen has done—to systems containing components not at all soluble in the crystalline state, or whether we use it in petrology in the extended sense in which it is used by physical chemists, that is, to cover all cases where we, after separation of any component initially occurring in surplus over the eutectic proportion, have a simultaneous crystallization of two or several components (chemical substances or mixed crystals).

Wahl therefore appreciates that there have been differences in the manner in which the word has been used, but I believe the quotation given hardly represents accurately the essential difference between his usage and that of Bowen. Reference to Bowen's original paper shows that his views were not based on the presence or absence of mixcrystals, but whereas Wahl applies the word "eutectic" to lines and surfaces, Bowen limited it to points.

In Wahl's criticism of conclusions of mine (p. 11), he supposes that they are "a consequence of the way in which rock systems containing mixcrystals have been dealt with." As a matter of fact, in the discussion to which he refers mixcrystals were only remotely involved, and not in such a manner as to affect the conclusions. In my use of "eutectic" I referred to an invariant point and not to a boundary curve or surface. This seems to have escaped Wahl's attention, and for this reason he evidently missed the bearing of the argument I was endeavoring to make.

The present purpose, however, is not to give a critical review of Wahl's article. It has been brought up for discussion only to illustrate the fact that there has been a decided difference among writers

[1] G. W. Morey would define a eutectic and would distinguish between a eutectic point and other singular points on phase diagrams as follows: "An invariant point in a condensed system at which a liquid and several solid phases coexist is called a eutectic when the composition of the liquid phase is such that it can be formed without remainder from the solid phases. For example, in a binary system the composition of the liquid is intermediate between that of the two solids; in a ternary system its composition is represented by a point inside the triangle formed by the three solid phases" (personal communication).

in the way that "eutectic" has been used. Reference to a number of other articles has made this even more evident, and has shown that some confusion of ideas and differences of opinion may probably be traced to this cause.

In order to ascertain what usage is recognized and sanctioned by authorities in physical chemistry and petrology, I have consulted a large number of standard textbooks, and have found considerable differences in this respect. Many authorities seem to apply the term "eutectic" only to a point, but others use it for lines and probably for surfaces. In some cases it seems as if a point were the idea in mind, but that the word were used to apply to conditions where, in actual fact, the crystallization must have taken place along boundary curves.

The word was first used by Guthrie, and there is probably no doubt that the relations he had in mind referred only to a point. In Findlay's "Phase Rule and Its Applications," reference is made to Guthrie's original article, and the eutectic point, for two-component systems, is stated to be the lowest temperature that can be obtained with mixtures of two components in presence of vapor. Similarly, for ternary systems, the eutectic point is given as the lowest temperature attainable with the three components. However, Findlay here goes on to speak of ternary eutectic *curves*, meaning the lines joining the binary eutectic points to the ternary point, and it is this extension of the original meaning that is accepted by a number of authors.

Wahl goes further than this in speaking of "eutectic surfaces," and in this usage the word has almost lost its original significance. It is a serious question whether all these extensions of meaning beyond the primary idea of a point are desirable. When used to mean a point, a eutectic has certain important and unique properties. At this point the temperature is fixed until crystallization is complete, and the total composition of the solid phases is exactly that of the liquid from which they crystallize. The system is invariant. So important are these properties and the consequences arising from them that if the meaning of the word is broadened to apply to other relations, there will be need of a new word to apply to the condition for which "eutectic" was originally invented. As some writers now

use it, it means little more than separation of crystals from a solution, and has no special significance. For this process we have the convenient terms "boundary curves" and "boundary surfaces" to express the idea simply and adequately.

For many years geologists have been speaking of eutectic structures and eutectic relations in igneous rocks. Several geologists have attached much theoretical importance to such relations, while others have been of a contrary opinion. It is evident that the word has been used with different meanings, and this accounts for part of the discrepancy, but there is indication that not only a confusion of terms but also to some extent a lack of definiteness of ideas is involved. Writers have spoken of eutectics as if they supposed the conditions they dealt with were represented by a point (analogies being drawn with systems in which the invariance of a point was the actual condition), and have neglected to recognize factors which change the relations from a point to a boundary curve. The most important of the modifying factors are the presence of volatiles and the presence of mixcrystals.

Whatever may be one's views as to the quantity of volatile ingredients present in magmas, it will probably be generally accepted that in many cases the volatiles have an important effect on the conditions of final crystallization. In some surface magmas the volatiles may escape so quickly and the magma cool with such rapidity that the resulting microcrystalline or cryptocrystalline aggregates cannot be profitably studied for evidences of eutectic relations. In other surface lavas the presence of a reek of vapor for a long period indicates a slower evolution of volatiles; but it is in plutonic magmas that the volatiles must have their greatest influence on crystallization. Whereas in laboratory melts a eutectic point may be attained at which the composition of the solids is the same as that of the liquid and the whole crystallizes at a fixed temperature, in natural magmas impregnated with volatiles the final crystals are deposited along a boundary curve of decreasing temperature and varying composition until the last of the volatiles escape or until a more or less dilute aqueous residue of the magma is attained.[1]

[1] In natural magmas there may be additional complications. We may recognize as theoretically possible three methods of formation of relatively dilute aqueous solutions from a plutonic magma:

1. By a *continuous* process, involving progressive crystallization and the produc-

Furthermore, most of the minerals crystallizing from magmas are mixcrystals or solid solutions of variable composition. This fact again causes final crystallization to be spaced over an interval of temperature rather than occurring at a eutectic point.

Now, when the term "eutectic" was used to refer only to a point, certain attributes were found to hold for this unique condition. With the extension of the meaning to crystallization along a boundary curve, there has plainly been a tendency to assume that the product still possesses these attributes.

This tendency is manifested in two principal ways:

When a simple two-component system crystallizes at a eutectic point (or, in fact, along a mixcrystal boundary), one of the chief factors which determine the proportion in which the two components shall appear in the solid is the heat of solution of each, which, in this case, is often not very different from the heat of fusion. This correspondence of heat of solution to heat of fusion may still hold for a three-component or even for a four-component system, but a magma is a very complex solution, made up of many ingredients, including water and other volatiles. Ionization, internal reactions, depression of temperature of solidification, and other disturbing factors enter the problem in such a way that the heat of solution is likely to be greatly modified, and the proportions in which the solid phases appear will be correspondingly altered. For instance, if two minerals crystallize from a dry melt at a eutectic point in certain proportions, we should not assume without definite evidence that they would crystallize from a plutonic magma or from a pegmatite liquid in the same proportions.

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tion of a more and more dilute aqueous residue. This is the only process ordinarily taken into consideration.

2. By a *discontinuous* process, in which the magma splits up at some stage into two immiscible liquids, one relatively dry and the other wet. This process is upheld by some geologists, and denied by others.

3. By a second *discontinuous* process, involving distillation of easily volatile substances (including water vapor and compounds of certain bases and of silica) from the hot magma to the cool walls, and recondensation. Few geologists have given much consideration to this process, and from lack of observational data there is a wide difference of opinion as to its quantitative importance.

The theoretically possible phenomenon of a critical end-point is a special case of this last process, but its actual occurrence in magmas is much less certain than is distillation of volatile compounds from a liquid magma in the ordinary way.

Second, it has been found that not infrequently the simultaneous crystallization of two or more substances (metals especially) at a eutectic point results in a peculiar graphic structure, which has been termed a eutectic structure. By extending the meaning of "eutectic" to the process of crystallization along boundary curves, the word carries over with it in its expanded significance the idea that graphic structures are to be expected from this process of crystallization also, and thus support is given, in an adventitious manner, to the argument that graphic structures in rocks may be assumed to be of eutectic origin. Before these arguments can be considered valid, it should be shown that the graphic structures are to be expected as the normal result of crystallization along boundary curves as well as at eutectic points, and that they are not likely to be formed by processes of wholly different character. In view of the evidences given by Sederholm[1] on the formation of myrmekites by secondary processes, and those given by Schaller[2] and others on the replacement origin of certain graphic granites, the second requirement is likely to be especially difficult to meet.

It should be noted that in the preceding discussion, and generally in discussions of the application of physicochemical principles to rock magmas, the relations considered apply to equilibrium conditions. The question of lack of equilibrium in the crystallization of magmas, and the modifications of theory thereby required, is important, but its consideration would lead us too far afield, and it is not directly involved in the matters to which it is desired to call attention.

Evidently the term "eutectic" has been applied in very different ways, and, in some instances, apparently without careful regard for factors which change the conditions of final crystallization from a fixed temperature to a range of temperature. For many reasons it seems desirable to return to the early significance of the word: that "eutectic" implies a certain unique point on a crystallization diagram; and to use the terms "boundary lines" and "boundary sur-

[1] J. J. Sederholm, "On Synantetic Minerals and Related Phenomena," *Commission Géol. de Finlande, Bull. 48*, 1916.

[2] W. T. Schaller, "The Genesis of Lithium Pegmatites," *Amer. Jour. Sci.*, Vol. X (1925), p. 270.

faces" for the appropriate geometrical elements of the diagram. Even if this does not appear desirable to all, at least no one will question the advisability of using the terms in such a manner that no doubt will be left in the mind of the reader as to what is meant; and of keeping clearly in mind the question as to whether the results we describe in a given instance are to be attributed to crystallization at a fixed point or along a boundary curve.

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THE LEVEL OF BASELEVEL

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ABSTRACT

The prevalent concept of the baseleveling process does not include the inevitable rise of sea-level which accompanies erosion of the lands in consequence of deposition of the resulting sediments in the oceans. Hence it does not fit the actual phenomenon. It is estimated that complete baseleveling of the present lands in the absence of diastrophism would result in a rise of sea-level in the neighborhood of 670 feet, due to displacement of sea-water by sediment. Add to this the effect of melting of the present polar ice-caps, and the rise of the sea would amount to about 725 feet. For the higher portions of the present lands, baselevel would come to be at about 725 feet above present sea-level, if diastrophism did not intervene. Present sea-level is far from being the level at which baselevel will theoretically come to be for the greater portion of the land masses. The problem of baseleveling is much more complicated than has been recognized.

In a recent discussion on baselevel, Dr. Douglas W. Johnson[1] deprecated use of the expression "level of baselevel,"[2] because it seemed to him to result in unnecessary confusion. Unnecessary complication, of course, is to be avoided. But, after all, is the actual case in nature as simple as most writers have seemed to imply? If the natural phenomenon is very simple, let us by all means employ simple terms; if, however, the actual phenomenon inevitably involves complex, variable factors, let us not scorn a more complicated nomenclature. But, in any case, a question of terminology is of slight importance compared with a correct understanding of the natural phenomenon itself and of the various factors which are involved. It is only because of the belief that the writers on baselevel have completely overlooked fundamental elements in the problem that this note is written.

Johnson has stated his conception of the best usage of the term "baselevel" in the following sentence:

> It seems desirable, therefore, in the interests of simplicity of conception and clarity of expression, to apply the name "baselevel" to the most significant surface with which the geomorphologist has to deal, the sea-level surface projected as an imaginary level plane under the lands.[3]

Powell's original definition included three ideas, general baselevel, what is now termed "grade," and local, temporary baselevels.

[1] Douglas W. Johnson, "Baselevel," *Jour. Geol.*, Vol. XXXVII (1929), pp. 775–82.

[2] As used in Chamberlin and Salisbury, *College Geology*, Part I, rewritten by R. T. Chamberlin and Paul MacClintock (1927), pp. 108–9.

[3] *Op. cit.*, p. 782.

The grand, or general, baselevel (with which we are here concerned) was conceived by Powell to be the level of the sea.[1] Usage in the years following Powell's analysis having become so varied, Davis proposed to restrict baselevel to the limit of subaerial erosion, which is stated to be "the 'level base' or 'baselevel' drawn through a land mass in prolongation of the normal sea-level surface."[2] This presupposes, of course, an undisturbed cycle. Davis says further:

Baselevel is complete from the beginning, and permanent to the end; grade is slowly introduced and gradually extended.—The conception of the general baselevel must be made at the outset as that of a completed surface extending beneath the land mass under consideration at the beginning of the cycle, and so remaining as long as the advance of the cycle continues undisturbed. In the ideal case, which provides the general scheme with respect to which all other cases are classified, the land mass once uplifted is supposed to stand still until it is worn flat. This supposition is so artificial and does so great violence to much that is known as to the behavior of the earth's crust that some students are therefore disposed to discard the scheme of the cycle altogether in the sculpture of land masses, overlooking the fact that however many movements of a land mass may be discovered, the many incomplete cycles that are separated by these movements must each be treated essentially according to the scheme of the ideal cycle. In every case, the processes of land sculpture, quickened or slackened in consequence of the new attitude given to the region, go on with respect to the new attitude of the baselevel within the land mass.

Even during the movement of the land mass, it must be conceived of as rising or sinking through a fixed and complete baselevel surface, with respect to which its carving is even then begun, and long afterwards continued, during the ensuing time of relative or absolute rest. Hence, for every cycle or partial cycle of erosion, the imaginary baselevel surface is immediately conceived as complete at the outset, and as thenceforwards remaining unchanged.[3] . . . . Baselevel remains fixed all through an uninterrupted cycle.[4]

Many other writers are in agreement, and this seems to be the current opinion. This concept is simple and clear, but is it correct?

THE ACCOMPANYING RISE OF SEA-LEVEL

As the lands are cut down by stream action, much of the material eroded from the land is deposited in the sea. By the time the land

[1] J. W. Powell, *Exploration of the Colorado River of the West and Its Tributaries* (Washington, 1875), p. 203.

[2] W. M. Davis, "Baselevel, Grade and Peneplain," *Jour. Geol.*, Vol. X (1902), p. 84.

[3] *Ibid.*, p. 91. [4] *Ibid.*, p. 95.

has been reduced approximately to baselevel nearly all of the material formerly above this level has been conveyed to the oceans.[1] Part of it has been laid down as sediment on the ocean bottoms, and part is in solution in the sea-water. Most of the mineral matter brought to the sea in solution is precipitated eventually in marine deposits. A portion of it, however, remains in solution, in the course of time gradually increasing the mineral content of the sea. But the mineral matter remaining in solution is small in amount compared with the volume of sediment shifted from the lands to the sea.

As the material eroded from the lands is deposited in the oceans, it displaces a corresponding volume of water and sea-level rises. R. D. George has estimated "that cutting away of the present continents, and the deposition of the material in the ocean basins, would raise the sea-level about 650 feet."[2] The method used in this estimate not being stated, it is not clear that the islands of the sea were included. Also twenty-five years of exploration have added to our knowledge of the area of Antarctica. Hence a new estimate was made on the following basis:

Total area of land	57,000,000 square miles[3]
Total area of oceans	139,500,000 square miles
Average height of land above sea-level	2,300 feet

For simplicity assume that the land areas rise in regular slopes from sea-level to 4,600 feet (Fig. 1). This, of course, can only approximate the actual case. But the topography and elevations of considerable portions of the globe are too poorly known to justify, in the present instance, the great labor which would be involved in any attempt to follow the actualities in detail. Besides, over the whole globe, the irregularities would tend strongly to average up. On this assumption there would be 8,302,000 square miles of land less than

[1] We will neglect such mineral matter as has been deposited in vein fillings and rock cementation beneath the baseleveled surface. This is to some extent offset by mineral matter removed from beneath the baseleveled surface by solution.

[2] Chamberlin and Salisbury, *Geology*, Vol. I (1904), p. 520. See also Vol. II (1906), pp. 231–32.

[3] Various estimates of the areas of land and sea have been made. Following the estimates of Kossinna, the *Encyclopaedia Britannica*, 14th ed. (1929), Vol. XVI, pp. 681 and 683, gives the total land area as 148,892,000 sq. km. and the total sea area as 361,059,000 sq. km. Essentially these figures are used in this article.

670 feet[1] above sea-level, and 48,698,000 square miles of land more than 670 feet above sea-level. The average height of the land above this 670-foot level would be 1,965 feet. Erosion of this would produce

$$\frac{48,698,000 \times 1,965}{139,500,000} = 686 \text{ feet rise of sea-level.}$$

but, rising thus, the seas would spread over the 8,300,000 square miles now between sea-level and 670 feet. Allowing an average depth of water of 335 feet over this area, this encroachment of the sea would be equivalent to 20 feet of water spread over the rest of the ocean. This correction reduces 686 feet to 666. Hence our estimate is that planing all the present lands down to the 670-foot level and

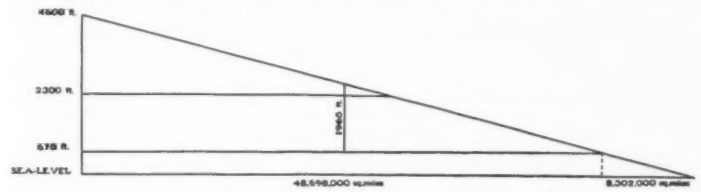

FIG. 1.—Diagram to illustrate method of estimating rise of sea-level in consequence of cutting existing lands down to a level 670 feet above present sea-level.

deposition of the eroded material as sediment on the ocean bottom would raise sea-level about 666 feet. For round numbers, let us adopt the figure 670 feet.

In this calculation no account has been taken of the land-derived mineral matter which remains dissolved in sea-water. Since we know that the total mineral matter now in solution in the oceans amounts to only 20 per cent of the volume of all lands now above sea-level,[2] or 15 per cent of the present land mass above the 670-foot level, and that this is the net accumulation from all the erosion cycles of geologic history, it is apparent that this factor can be ignored in the treatment of any single baseleveling without involving any error of consequence.

The estimate also takes no account of possible rise of the land areas in consequence of denudation. This at present cannot be evaluated. But the very fact that a high state of peneplanation has been

[1] Figure selected as result of several trial calculations.

[2] Chamberlin and Salisbury, *College Geology*, 1927 edition, p. 231.

developed repeatedly in the past without erosion to excessive depths, or very great apparent uplift during peneplanation, leads the geologist to assign a minimum value to this consequence of erosion. This qualifying factor, however, should be kept in mind, though here grouped with diastrophic movements which are not considered. Probably of less importance is a slight lowering of sea-level near the lands due to lessened gravitative attraction of the reduced land masses.

If there is no diastrophic disturbance of the lithosphere and no volcanic outpourings of great consequence during baseleveling, the baseleveling process itself by depositing sediments in the oceans will cause a rise of sea-level in the neighborhood of 670 feet. Before baseleveling is complete, diastrophism and extrusive vulcanism are likely to intervene, notably altering sea-level, but we are concerned here only with the baseleveling process itself.

ADDITIONAL EFFECT OF DISAPPEARING ICE-CAPS

Present climatic conditions are somewhat exceptional, and the large polar ice-caps now existing in Antarctica, Greenland, and elsewhere further complicate the problem. During times of reduced lands and wide-spreading epicontinental seas, mild and more equable climates have prevailed as a rule in the geologic past. Hence with reduction of the lands toward baselevel, melting of the ice-caps would be expected. This would increase the water of the oceans and raise sea-level. The amount of such sea-level rise may be estimated as follows: Take 6,000,000 square miles to be the area of the present ice-caps and assume that the average thickness of ice over this area is 2,000 feet.[1]

Then $\frac{6{,}000{,}000 \times 2{,}000}{139{,}500{,}000 + 9{,}000{,}000^{2}} = 81$ feet rise of sea-level due to melting of ice-caps.

Let us now make another estimate for the rise of sea-level resulting from cutting present lands down to a level at 725 feet, instead of 670 feet, above present sea-level. The result is 642 feet rise of sea-

[1] Figure selected after consultation with Griffith Taylor.

[2] Area of land now less than 725 feet above sea-level, which would be covered by seas spreading in consequence of cutting lands down to a level 725 feet above present ocean surface.

level due to displacement of sea-water by sediment alone. Therefore $642+81=723$ feet rise of sea-level due to sediment and melting of present ice-caps combined. Hence our final conclusion is that baseleveling the present lands should, by itself, result in a rise of sea-level to the extent of about 725 feet, and that baselevel for the higher portions of our land masses should come to be in the neighborhood of 725 feet above the level of the present seas.[1]

INADEQUACY OF CURRENT CONCEPTS

Geomorphologists define baselevel in terms of *present* sea-level. According to prevalent opinion, baselevel is the present sea-level surface projected as an imaginary level plane under the lands. But as just shown, the very process of baseleveling itself raises the level of the sea just as surely as it lowers the surface of the land. The two are inseparable, ignoring diastrophic and volcanic activity. Sea-level can remain the same during baseleveling, *only* when diastrophic or other changes occur which exactly compensate the volume of sediment deposited in the sea, the increase in sea-water from melting of ice-caps and other causes, and the diminished gravitative effect of the reduced land masses. Such a coincidence would be improbable, though appeal can be made to the overworked principle of isostasy to make some partial compensation seem plausible. Any other diastrophic activity, or lava flows on the ocean floors, would only complicate the problem still more.

Hence *present* sea-level is only one of the factors determining the level at which baselevel will develop, except possibly for areas which are now not far from sea-level. Present sea-level is not the limiting base for subaerial denudation of the lands as a whole, and the "projected sea-level plane" does not fit the case.

Consider an area like Colorado, high and far from the sea. If no diastrophism complicated the problem, and all other lands of the globe were also brought to baselevel, that level in Colorado would eventually be in the neighborhood of 725 feet above present sea-level. That would be higher above the present sea-level than is the greater part of the state of Illinois today. And it would be the result

[1] Any increase in the total volume of sea-water by excess of water from volcanic exhalations, etc., over that uniting with rock material in the process of hydration, would further complicate the problem.

of the baseleveling process alone. But Colorado today is not being eroded with respect to this 725-foot level. This level can only play an effective part in the baseleveling process in the remote future when the lowering surface of Colorado is approaching the rising surface of the sea in the later stages of baseleveling. It is not functioning today.

Suppose that no diastrophic change affected North America during the baseleveling, but that the continent of Asia, for example, was strongly uplifted while baseleveling was proceeding undisturbed in North America. In this case, baselevel in Colorado would finally come to be, not at 725 feet above present sea-level, but at some different level, because of the increased volume of sediment poured into the sea by greater erosion in Asia. Even though North America remain still-standing, any notable diastrophism during the time of baseleveling, anywhere else on the globe (unless the effects of uplift in some places just compensate those of subsidence in others), would cause eventual baselevel in Colorado to be at some other level than the estimated 725 feet. The complications are obviously very great.

In short, the level at which baselevel will come to be cannot be predicted for an area like Colorado, nor for most other areas. It is dependent on far too many variables. A definite baselevel for Colorado, or for most other areas (except for local, temporary baselevels), does not exist today. That level will be determined by what takes place on the globe between now and a postulated future baselevel stage. In the later stages of peneplanation, the sea-level *at that time* will be the governing level, but as time goes on and the peneplain is reduced further toward baselevel, sea-level will continue to change correspondingly. Apparent baselevel will be changing in level. If the process could go on to completion, baselevel for a given place would be the *surface corresponding to sea-level at that place at the time of completion.*

Because the level at which baselevel may theoretically come to be in any given case in the future depends on so many variable factors, it is thought that the expression "level of baselevel" is not without justification. Possibly "baselevel" will do just as well. But the writer believes that the single word "baselevel" is likely to give too fixed and definite a concept, as it has in the past. Baselevel in nature is

potential and shifty. In any case the expression "level of baselevel" is much simpler than the exceedingly complex natural phenomena which determine that level.

MINOR CONSIDERATIONS

Objection to the commonly used phrase, "sea-level *plane*," should perhaps also be made. Peneplains and baselevels are convex surfaces developed on the spheroidal earth. They are approximately spheroidal rather than plane, if of any considerable area. Even over small areas and even though perfectly level, as determined by spirit leveling, they cannot coincide exactly with any spheroidal surface, for the most part. The density of the rocks varies considerably from place to place. Hence a perfectly "level" surface on the earth (everywhere perpendicular to the plumb-line) is an irregular surface, the irregularities depending on the varying specific gravity of the underlying rocks.

Terminology, however, is but a minor consideration in this article. The quite varied usage of the term "baselevel" in the past has been well presented and discussed by Malott.[1] But however much the different writers vary among themselves in their interpretation, apparently one and all of them thus far have overlooked one of the most vital factors in the problem, namely, the accompanying rise of sea-level in consequence of degradation of the lands. Interpreted in the light of the fuller problem, baselevel in the sense in which it is used by the majority of writers loses much of its fixity, much of its definiteness, and probably, in consequence, not a little in relative importance. The selection of a satisfactory definition of baselevel, however, may well be left to the specialists in that field.

[1] Clyde A. Malott, *Base-Level and Its Varieties*, "Indiana University Studies" (1928), Vol. XV, No. 82, pp. 37–59.

THE PRE-CAMBRIAN GREENSTONE COMPLEX OF THE JEROME QUADRANGLE[1]

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ABSTRACT

In the Jerome quadrangle are a series of greenstones varying in composition from andesites to rhyolites, principally the former, which are pre-Cambrian in age. Heretofore these greenstones have been included with the Yavapai schist series, but detailed mapping shows them to rest unconformably on the upturned and eroded edges of the schist. The greenstones are therefore younger than the typical Yavapai schists and are believed to be older than the Grand Canyon series. The structural features of this complex and the contact action of the pre-Cambrian granitic masses are also described in this article.

INTRODUCTION

An examination of a geologic map of Arizona will show that areas of pre-Cambrian rocks of that state are almost entirely confined to the mountain and desert provinces as defined by Ransome.[2] Such exposures occur in isolated ranges, largely of the fault-block type, and separated by basins in which late Tertiary and Quaternary sands and gravels have accumulated. In many ranges, especially in the southwestern portion of the state, granitic rocks prevail; and, as such intrusions are overlain by Paleozoic sedimentary rocks in but few places, the pre-Cambrian age of the intrusive rocks is, therefore, in doubt. Some of them correspond to granodiorite in composition, and it is not impossible that they are genetically related to the great batholithic intrusions of Mesozoic age extending from Lower California to Alaska.

Detailed studies of local areas of metamorphic rocks are recorded in numerous publications of the United States Geological Survey, and such schistose rocks are usually assigned a pre-Cambrian age. The separation of these recrystallized rocks into definite formations; the unraveling of the complex pre-Cambrian history; and the correlation of definite horizons or formations from one mountain range to another are extremely difficult because of the isolated character and small size of the exposures of such rocks.

[1] Published by permission of the director of the Arizona Bureau of Mines.

[2] F. L. Ransome, "Geologic Atlas," *Globe Folio*, No. 111 (1902).

During the course of an examination of the geology of the Jerome quadrangle for the Arizona Bureau of Mines, a new group of formations was discovered, which is clearly younger than the older metamorphic rocks, locally known as the Yavapai schist, and apparently younger than the Grand Canyon series.

LOCATION

The Jerome quadrangle is bounded by north Lat. 34°30′ and 35°00′, and Long. 112°00′ and 112°30′ west of Greenwich. The most prominent mountain mass, the Black Hills, is nearly centrally located within this quadrangle. The name "Black Hills," however, is a misnomer, for the difference in elevation between Mount Mingus, the highest point in the range, and the Verde River on the east is over 3,500 feet. From the standpoint of scenic beauty and depth to which this river has cut its bed, the Verde Valley rivals, in a small measure at least, the famous Grand Canyon of the Colorado.

On the east side of the Black Hills are the important copper deposits of the Verde District at Jerome. From Jerome southward the greenstones flank the range, form a continuous belt around the southern end of the mountains, and extend several miles northward on the west side.

GEOLOGY

In the area considered in this article are exposures of typical Yavapai schist, greenstones, and intrusive masses of granitic rocks. All these formations are pre-Cambrian in age. Resting on the eroded surface of these older rocks are nearly horizontal sedimentary rocks belonging to several subdivisions of the Paleozoic era. Capping the range are Tertiary basaltic flows, and in the valley on each side of the mountains are late Tertiary or Quaternary gravels and sands.

Yavapai schist.—The type locality of the Yavapai schist is in the Bradshaw Mountains quadrangle which joins the Jerome sheet on the south. They have been mapped and described by Jagger and Palache[1] in the *Bradshaw Mountains Folio*. A belt of these schists extends northward into the Jerome quadrangle.

On the west side of the Black Hills is a narrow but continuous

[1] Jagger and Palache, "Geologic Atlas," *Bradshaw Mountains Folio*, No. 126 (1905), pp. 1–3.

belt of Yavapai schist that occurs at the base of the mountain as shown on the geologic map (Fig. 1). This belt extends a short distance north of Yaeger Canyon to where the formation is covered by flows of basalt.

Quartz-sericite schist and brown slate are the most common varieties of rock in this formation, although more or less chloritic schist of a pale to dark greenish color was also observed. In the brown slates are numerous thin layers of impure, dolomitic limestone of a buff color. Few of the individual beds are over 6 inches thick and most of them are under 3, and with thin partings of slate. There is more or less of a gradation between the slates and the quartz sericite schists, and between mica schist and conglomerate. Between Yaeger Canyon and the Shylock mine, this belt of conglomerate is at least 60 feet wide. In it the pebbles are well rounded and small, few exceeding 1 inch in length. They consist, very largely, of quartz, quartzite, dark brown, and black jasper, gneiss, and a silicified felsite. The matrix between the pebbles is schistose and is composed of quartz and white mica. The mica flakes occur in curved bands surrounding each pebble. They lie with the long direction parallel to the schistosity, but do not appear to have been deformed by the dynamic forces that produced the schistosity. Less than a mile west of the Shylock mine are bands of granite gneiss in the metamorphic series.

The schistosity strikes nearly north-south and parallels, more or less, the bedding planes of the limestones. A close inspection of the slates, however, shows that crumbling and contortion exist in these less competent rocks. The dip of the schistosity is usually at steep angles and to the west, and sometimes is vertical.

Most of the schistose rocks of this series in the Jerome quadrangle are certainly sedimentary in origin. The presence of beds of limestone in the slates points to a sedimentary origin for both rocks. The pebbles in the conglomerate indicate a sedimentary origin for that band; and, as it grades into quartz mica schist in which occasional strings of rounded pebbles may be seen, it is possible that this variety of schist was also derived entirely from water-laid material. The chloritic schists are probably largely, if not entirely, formed from igneous material having the composition of andesite. All evidence of original igneous textures has been destroyed during

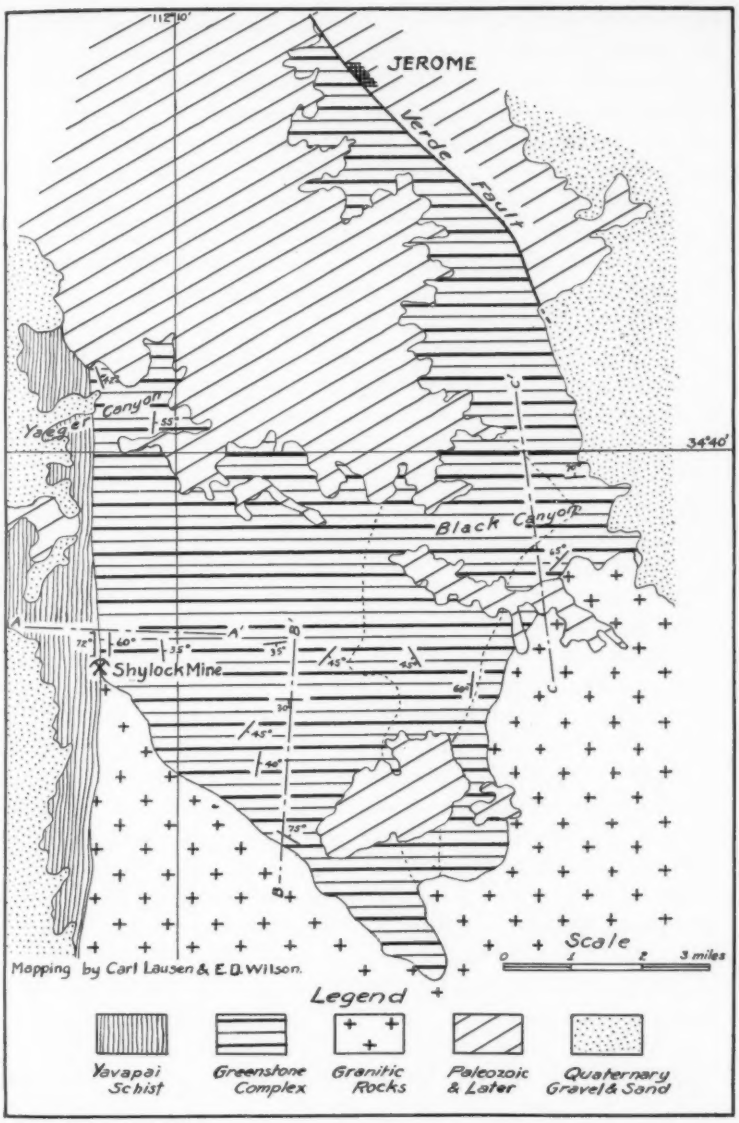

FIG. 1.—Geologic map of the greenstone complex south of Jerome, Arizona

recrystallization, but the faint banding of different shades of green is suggestive of beds of volcanic ash.

Greenstone complex.—Resting on the eroded surface of the Yavapai schist described in the preceding section is a series of volcanic flows, tuffs, and agglomerates together with more or less sedimentary materials. Locally, as at the United Verde mine or near intrusive bodies, the greenstones are more or less schistose and have been included, heretofore, as a member of the Yavapai schist.[1] On the west side of the Black Hills, however, and a short distance north of the Shylock mine the unconformable relations of the two formations are clearly evident. At this locality there is a decided difference in the physical character of the two formations; the lower is thoroughly recrystallized and schistose, while the basal flows of the greenstone are massive and show no evidence of dynamic stresses other than deformation into a series of folds. The relations of these two formations are so evident that it is surprising that this fact has been overlooked for so long, although a number of geologists have made examinations in this region.

The prevailing color of the rocks comprising the greenstone complex is a dark green to black, and the more acid flows are mostly dark brown. The tuffaceous members are generally a paler green and nearly always show distinct bedding. The flows most commonly observed are andesites, but latites and rhyolites were also found, and trachytes may be present. However, the highly altered condition of some of the rocks makes an accurate classification difficult. The texture and the mineral composition show considerable variation; for the rock may be holocrystalline and fine-grained, or porphyritic, and in the latter variety the phenocrysts may occur in a visibly crystalline or stony groundmass.

In a thin section the andesites invariably show more or less alteration; but sufficient remnants of the primary silicates remain to enable one definitely to classify the rock. Primary minerals identified are predominantly plagioclase feldspar ranging from andesine to labradorite in composition, occasional grains of orthoclase more or less altered to kaolin, shreds of green hornblende, and deep brown biotite. There are a few small grains of quartz, perhaps primary,

[1] Louis E. Reber, "Geology and Ore Deposits of Jerome District," *Trans. Am. Inst. Min. & Met. Eng.*, Vol. LXVI (1921), pp. 3–26.

and in some slides numerous thin needles of apatite. Alteration products are chiefly secondary quartz, calcite, and epidote in the plagioclase feldspar, while the orthoclase has been changed to a feltlike mass of sericite and kaolin with some quartz. The original ferromagnesian silicates have been replaced by chlorite and a little serpentine.

Associated with the andesites, but at some distance above the base, are flows that are light gray to nearly black and in some cases of a brownish or purplish tinge. Such flows are often porphyritic, and the phenocrysts are chalky in appearance. When examined with the polarizing microscope such phenocrysts are nearly all orthoclase somewhat altered, but a few clear crystals of an acid plagioclase are present. The groundmass in which these phenocrysts occur is composed of numerous small laths of feldspar. They show more or less of a parallel arrangement suggesting a flow texture. Decomposition products are so abundant in the groundmass that an accurate determination of the minerals present is impossible. These small feldspar laths may be orthoclase and the rocks would then be typical trachytes. The small amount of quartz observed is probably secondary in origin.

The rhyolites and latites are most common in the region near Black Canyon (see Fig. 1). The dotted line on the map shows the approximate boundary between the prevailingly acid and more basic types of flows. These acid flows are believed to be the latest members of the greenstone complex exposed in this region.

Both rhyolite and latite are stony in appearance, and show visible phenocrysts of either feldspar or quartz. The rhyolites are some shade of brown in color whereas the latites are gray to black. Both types of rock contain variable amounts of orthoclase and acid plagioclase. Quartz occurs as fairly large, rounded, or embayed grains in the rhyolites, and as insignificant grains in the latites. Brown biotite, nearly always altered, is the prevailing ferromagnesian constituent, and in the latites a little chlorite was seen. The groundmass of these rocks is rather interesting. The stony appearance suggests that more or less glass may be present; but a microscopic examination shows that devitrification has set in, and a vitrophyric texture developed. This texture, however, is most common in the rhyolites.

The tuffs associated with the acid and more basic flows are highly indurated rock. They usually show distinct bedding. Some of the material included by Reber[1] in the "bedded sediments" is probably pyroclastic in origin. These tuffs show all gradations to fragmental rocks or explosion breccia.

Sedimentary material is not abundant but does occur in places between flows. The variety most frequently seen is quartzite, although argillites are also present. These rocks are characteristically some shade of gray and the argillites are usually well banded. They are so thoroughly indurated that they often break across rather than parallel to bedding planes.

Intrusive rocks.—Various intrusions cut the greenstone complex. Along the south boundary such intrusive rocks are essentially granodiorites. At the United Verde mine they are augite diorite and quartz porphyry, and the latter is the older of the two. The augite diorite forms irregular bodies of small size, although the main intrusion of this rock at the United Verde mine is covered to a certain extent by Paleozoic sediments and has not been explored sufficiently underground to determine its size. The lack of contact metamorphism suggests that it, too, may be small. At the south end of the greenstone complex, as shown on the map, the intrusions are of batholithic proportions, and the contact action is very pronounced. Numerous dikes of diorite porphyry traverse the greenstones and are apophyses of the larger intrusion. They have produced no visible contact effects other than a slight baking.

STRUCTURAL GEOLOGY

Compressive stresses, regional in origin or due to the intrusion of granitic magmas, have developed a series of folds in the greenstone complex. There has also been more or less faulting, but whether or not this faulting antedates the folding is uncertain. Some faulting is believed to have occurred before the deposition of the Paleozoic sediments, and later faulting not only displaces the Paleozoic rocks but also the Tertiary basalts.

Section A–A′ is a short distance north of the Shylock mine. It was at this place that the relative positions of the Yavapai schist and

[1] *Op. cit.*, p. 12.

the greenstone were first determined. The section brings out these relations.

A north-south section was drawn through the contact of the greenstones with the granodiorite, and the folding of the beds by this intrusion is shown. As similar folding also occurs on the east edge of the greenstone, these relations would suggest that the south end of the greenstones forms a syncline with a pitch to the north or northwest.

A section across Black Canyon, C–C′, is included to show how the rhyolitic flows have been folded in with the more basic one, and

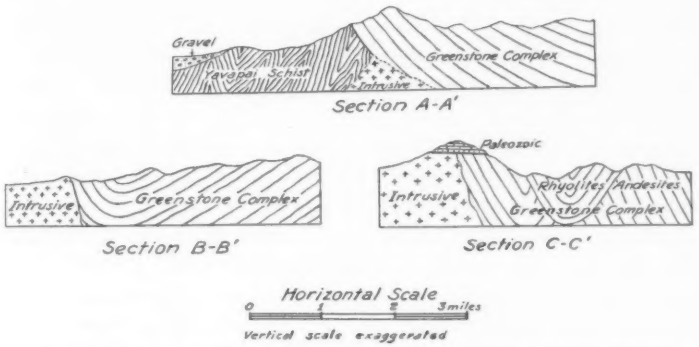

FIG. 2.—Structure sections of the greenstone complex south of Jerome, Arizona

leads to the inference that the acid flows represent the latest phase of volcanic activity in the greenstone complex in this region.

The acid flows rest on the andesite flows at Black Canyon and, to the westward, on the sedimentary rocks which are most abundant near the top of the andesites. The structure in the underlying rocks does not fit in well with the folding in the rhyolites. It appears, therefore, that the andesites and associated sediments were folded somewhat before the outpouring of the rhyolites; or else the acid flows spread out over a rough topography. In either case there would be a time interval between the eruption of the extreme types of rock.

The greenstone complex, therefore, is a group of two formations, one moderately basic and the other acidic. The sedimentary material must be included with the andesites.

Estimates of thickness are difficult to make in rocks where fault-

ing may have occurred, because of the similarity of the flows. In a section showing least disturbance, the andesites have a minimum thickness of 5,000 feet. Above them are approximately 1,500 feet of sedimentary material with some flows. The acidic flows are at least 2,000 feet in thickness.

METAMORPHISM

All the rocks comprising the greenstone complex have suffered more or less change; the andesite largely to an aggregate of secondary minerals; the rhyolites and latites by devitrification; and in the quartzites, a siliceous cement has probably taken the place of a calcareous one. But the more pronounced change occurred where the rocks have been subjected to intense compression or high temperatures.

At the United Verde mine the flows and associated rocks have been changed to sericite and chlorite schists. The schistosity in some cases parallels the contact of the diorite and in other cases does not. The edge of diorite, which is of finer grain, is often also quite schistose. On the lower levels of an adjoining mine, the United Verde Extension, an interesting change in the character of the greenstone is readily observable. As one goes away from the diorite contact the schistosity becomes less pronounced, and finally the rocks become as massive as those examined on the west side of the range near the Shylock mine. A similar feature may be seen on the surface by traveling in a southerly direction from Jerome.

The close association of the schistose phases with the diorite suggests that this intrusive was partly or perhaps largely responsible for the recrystallization. Thermal effects, however, are not readily noticeable, and the black schist closely associated with the ore is due to hydrothermal solutions which formed the mineral deposits.

At the contact with the granodiorite in the southern part of the area the greenstones have been changed to paragneisses by the heat and pressure of the intrusion. The andesites have been metamorphosed to hornblende gneisses, while the quartzite have formed quartz-biotite gneisses. The contact effects are visible over a distance of 1,000 feet from the edge of the intrusion and gradually die out at greater distances.

AGE RELATIONS

Capping the greenstones and the various intrusive rocks is a reddish sandstone. This sandstone grades through shaly beds into Devonian limestones. The sandstone is unfossiliferous, but sufficient fossils have been found in the limestone to determine its age. On the basis of lithogical similarity and stratigraphic position, Ransome[1] has correlated this formation with the Tapeats sandstone of the Grand Canyon section in which upper Cambrian fossils have been found.

At the base of the reddish sandstone in the vicinity of Jerome is a conglomerate which, locally, may be absent. The pebbles in the conglomerate, in part, were derived from the rocks upon which it rests. The old surface upon which the conglomerate rests is deeply weathered, oxidized, and stained reddish with iron salts. The unconformable relations are, therefore, self-evident.

The greenstones are intruded by granitic rocks and are therefore older, but to the northwest of Jerome and in the vicinity of Del Rio are massive beds of quartzite also pre-Cambrian in age. They rest on the eroded surface of the granite. These quartzites have been described by Wilson.[2] It is possible this formation is the equivalent of the Shinumo quartzite[3] of the Grand Canyon series, or may even be older. This series of rocks has been assigned to the Keweenawan by Walcott.[4]

Although the greenstones are not actually in contact with the Mazatzal quartzite, they are, however, believed to be older, chiefly because of the relations of the two formations to the granitic intrusives. If this supposition is correct, then the greenstone complex forms a group which is younger than the Yavapai schist and older than the Grand Canyon series, and adds a new chapter to the pre-Cambrian history of Arizona.

[1] F. L. Ransome, "Some Paleozoic Sections in Arizona and Their Correlation," *U.S. Geol. Survey Prof. Paper 98-k* (1918), pp. 159–61.

[2] Eldred D. Wilson, "Proterozoic Mazatzal Quartzite of Arizona," *Pan-American Geologist*, Vol. XXXVII (1922), pp. 299–312.

[3] L. F. Noble, "The Shinumo Quadrangle, Grand Canyon District, Arizona," *U.S. Geol. Survey Bull. 549* (1914), pp. 37–55.

[4] C. D. Walcott, "Pre-Cambrian Igneous Rocks of the Unkar Terrane, Grand Canyon of the Colorado, Arizona," *U.S. Geol. Survey Ann. Rept.* 1892–93, Part II, p. 508.

FURTHER EVIDENCE OF KEYSTONE FAULTING

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ABSTRACT

A new example of keystone fault illustrating the special features of this type better than any hitherto seen was recently found 30 miles north of LaTuque, Quebec. This example clearly answers some of the criticisms which have been brought against the theory. The converging joints can be seen and the intervening block has dropped about 25 feet.

The term "keystone fault"[1] was used by W. O. Crosby for narrow trough faults in which it was evident that the keystone or downfaulted block had dropped suddenly, both sides at one time and not first on one side and then on the other, as was probably the case with the larger grabens. A keystone fault is formed when two nearly parallel master-joints, converging slightly downward, are momentarily opened by tensile stress during earth movements. Repeated movement allows the block to sink deeper and to be often crushed to some extent by the closing of the jaws of the vise upon the keystone. A number of examples of this type of fault were described, all from New England, because the authors were most familiar with that region.

Since the publication of that article a criticism has appeared in a paper by Stephen Taber entitled "Fault Troughs."[2] This is to the effect that it is difficult to understand why the phenomena should be so plentiful in New England, where the seismicity is relatively low, whereas they have not been observed in regions of high seismicity, such as central and southern California, and that it is unfortunate that, in the type examples, there is no positive evidence of downward displacement.

Since it is known that severe earthquakes have occurred in New England in historic times, the fact of such occurrences rather than their frequency is what is essential to the problem. Had other re-

[1] W. O. and Irving B. Crosby, *Bull. Geol. Soc. Amer.*, Vol. XXXVI (1925), pp. 623–40.

[2] *Jour. Geol.*, Vol. XXXV, pp. 577–606.

gions come under the close observation of the authors at the time of the development of the keystone-fault theory, it is probable that chasms of this nature, which those not familiar with this type of fault have explained in other ways, might have been recorded as keystone faults. But now the best answer to these criticisms is to be found in a new example of keystone fault which is outside of New England and which shows positive evidence of downward displacement. This was recently found by the writer on the west bank of the St. Maurice River some 30 miles above LaTuque in the province of Quebec. The exact location is $3\frac{1}{2}$ miles above the mouth of Rivière au Lard.

The striking features of this keystone fault are that the converging master-joints can be seen, that the keystone itself has resisted crushing and stands up in the chasm with a fissure on either side, and that the downward displacement can be seen and measured.

The keystone block is triangular in ground plan with the apex at the eastern and lower end. This end of the keystone has dropped about 50 feet. The upper or western end of the keystone is about 100 feet wide, and the downthrow is only 10 feet and becomes still less a little farther west where the keystone block can barely be distinguished from the adjacent hillsides. The length of the keystone is about 300 feet. It is bounded on the south by a fissure 10–30 feet deep and on the north by a depression of less depth. Near the eastern end of the keystone the border joints show up well. On the south side of the southern fissure is a well-defined, smooth joint surface dipping 65° N., with a strike of approximately N. 45° E. The joint surfaces on the north side of the north depression are less regular, but the joints which appear to govern this side of the keystone strike N. 80° E, and dip 80° N. These bordering joints are thus plainly converging downward, with an angle of 15°, and their separation, even by small amounts during earth movements, would allow the settlement of the keystone. The angle between the strike of the joints governs the shape of the keystone and causes it to be triangular. The border joints are more nearly parallel at the western end of the keystone and may be traced for some distance beyond the end of the chasm. This keystone ends to the east by the convergence of the two border joints; to the west the amount of down-

throw becomes less and the keystone fault dies out. This condition has been observed in other keystone faults and is evidently a not uncommon mode of termination of these faults.

The rock in which this keystone fault was formed is quartz diorite gneiss, and its structure has a low dip to the north.

Below the eastern end of the keystone block the chasm continues as a small gorge to the shore of the St. Maurice River. Directly opposite, on the east side of the river, is a straight, narrow valley which may mark the continuation of the keystone fault as a single fault.

The fissures which bound the keystone on the two sides are singularly free from glacial drift although glacial boulders do exist on the surface of the keystone block. These are boulders which were on the surface and were carried down with the keystone. If this chasm had been formed prior to the glacial period the fissures would have been filled with glacial drift, and the absence of drift is strong evidence that the formation of this keystone fault occurred in postglacial times.

Like many of the other examples of keystone faults, this one is transverse to the direction of ice movement, its axis being approximately N. 65° E., and it is therefore clearly not a product of glacial erosion. The chasm was also not caused by stream erosion, as is shown by its peculiar character, so different from that of an erosion valley. It is now occupied by a very small stream, and there is no evidence that a larger stream ever flowed through it. The diastrophic origin of the chasm is further indicated by the shattered condition of the rock in the walls and immediate vicinity of the chasm.

This new example establishes the points about which there has been some doubt and makes clear that at least some of these peculiar, precipitous-walled chasms were formed by the separation of master-joints. The type is therefore a distinct one and worthy of recognition by the descriptive name of "keystone fault."

REVIEWS

Geologic Nomenclator. Compiled under the auspices of the Geologisch-Mijnbouwkundig Genootschap voor Nederland en Koloniën, under the editorship of L. RUTTEN. Quarto; pp. 338. The Hague: G. Naeff, 1929.

This volume promises to prove one of the most useful aids to geologists the world over that has recently appeared.

In 272 pages it presents in parallel columns the corresponding technical geologic terms in use in Dutch, German, English, and French. These are classified in sections under the major captions of:

I. Exogenic Processes and Physiography. Compiled by Boerman and Oestreich.
II. Tectonic Geology. Compiled by Molengraaff.
III. Volcanology. Compiled by Escher.
IV. Seismology. Compiled by Van Dijk.
V. Slow Changes in Levels and Mountain Building. Compiled by Rutten.
VI. Stratigraphy and General Paleontology. Compiled by Kruizinga.
VII. Petrology. Compiled by Grutterink.
VIII. Ore Deposits. Compiled by Grondijs and Schouten.

The materials under each of these major headings are classified under minor headings; thus under "Exogenic Processes and Physiography" there are nine subheads such as "Oceanography," "Coasts and Islands," "Weathering," etc. The literature consulted in preparing most sections of the *Nomenclator* is listed.

The last 57 pages of the volume are devoted to four alphabetical Indexes in the four languages covering all of the terms listed in the comparative tables.

The *Nomenclator* makes it possible for the geologist reading in languages other than his own to dispense with a dictionary in as far as technical terms are concerned and gives him much more authoritative data than most dictionaries contain.

E. S. B.

Annotated Bibliography of Economic Geology. Vol. I, 1928. Edited by JOHN M. NICKLES. Pp. 380. Lancaster, Pa.: Economic Geology Publishing Company. $5.00.

There are 1,756 titles listed, most of which have annotations. More than half of these are concerned with fuels and geophysical prospecting.

Metals are divided into five headings, and non-metals (except fuels) into three. Water, soils, engineering geology, areal geology, mineralogy and petrography, technique, and general, are the other headings. An apparently complete Index adds greatly to the value of the volume.

At first glance there appears to be little order in the arrangement of titles under a given heading, except in the case of petroleum. However, examination discloses that in many cases more or less general works are covered first, followed by an areal grouping. It is to be regretted that more headings were not used in indicating the order of listing to facilitate reference. The 224 titles under geophysical prospecting are presented alphabetically by authors; this duplicates the Index, and it would seem that subdivision by methods would be of much greater value. While the main purpose of the volume is to aid in keeping up with the recent literature, possible future use in the preparation of bibliographies from previous numbers should be kept in mind. The publication of comprehensive indexes at perhaps five-year intervals would be of great value in this connection.

The work is presumably published mainly for the use of American geologists. With this in mind, would not the unannotated titles of articles in easily available American publications suffice? In many cases the abstracts are published with the original papers, and need not be reprinted. Space thus released could be given with advantage to more detailed summaries of material which is less readily available to American readers, particularly to articles in foreign languages. Where maps are listed, their scales should be given, or at least some idea of how generalized or how detailed they are. This is done in some cases, which brings forth the hope that in the future each article described will be covered in fashion sufficiently detailed to be of real value. Fortunately, this is true of most of the material in the present volume.

The foregoing comments are offered in what is meant to be a helpful rather than a fault-finding spirit. The attainment of near-perfection is not sudden, and the present volume reflects great credit on its makers, under the chairmanship of Professor Lindgren. Most active American geologists will find this publication indispensable, and it is urged that all subscribe to this semiannual work to insure the continued success of the undertaking.

D. J. FISHER

Stratigraphical Paleontology. By E. NEAVERSON. London: Macmillan Co., December, 1928. Pp. 525; figs. 70.

Stratigraphical Paleontology, subtitled *A Manual for Students and Field Geologists*, is somewhat more restricted in its scope than its title indicates.

Its author, who is Demonstrator and Lecturer in Paleontology at the University of Liverpool, has given a detailed and valuable account, not of stratigraphical paleontology in general, but of the stratigraphical paleontology of the British Isles. He has not pointed out the relationships of the British faunal and stratigraphic successions to those of North America or even of the Continent. The volume, however, will be of great value to the average British geologist, and will be an important tool in the hands of those American and European students who are interested in effecting far-flung correlations.

The book is divided into two parts. Part I, entitled "General Considerations," is made up of seven chapters, as follows: "Introduction," "Morphological Features of the Chief Fossil Groups," "Preservation and Occurrence," "Faunas in Relation to Habitat," "Geographical Distribution and Migration," "Fossils as Indices of Horizon: Plants and Invertebrate Animals," and "Fossils as Indices of Horizon: Vertebrate Animals." Part II, entitled "Faunas of the Geological Systems in Britain," is composed of thirteen chapters dealing with the various systems and their faunal successions.

Part I contains a great deal of valuable information never before assembled in one volume, but the chapter dealing with morphology is at best only a sketchy synopsis, which might well have been omitted. Those who will use Part II as a reference work presumably are sufficiently well grounded in paleontology to need no such review, and beginners in the science undoubtedly will turn to the standard texts for their initiation. The chapter on morphology also unaccountably lacks a reference list, though all the other chapters of the volume are followed by rather complete lists of the British literature available on the subject. In most cases, however, these lists do not include important French, German, or American works. Part II is illustrated by figures of about 500 characteristic fossils. Most of these are well chosen for their value as index fossils, but some relatively uncommon species are included, and a few important forms are not illustrated. Most of the plates are very good, but a number of the drawings have been made with a heavy hand and leave something to be desired. In lieu of a general Index there is included an alphabetic list of genera and species, and an index of stratigraphical terms.

Stratigraphical Paleontology, although lucidly written, probably will not lend itself to use as a textbook even in England. Its value as a reference work, however, should recommend it to all teachers and students of biostratigraphy.

CAREY CRONEIS

Geologie von Peru. By G. STEINMANN (Bonn). With contributions from R. STAPPENBECK (Werder), "Nutzstoffe"; SIEBERG (Jena), "Erdbeben"; C. LISSON (Lima), Geologische Karte. Heidelberg: Carl Winters Universitätsbuchhandlung, 1929. Pp. xii+448; figs. 271; pls. 9; map 1. M. 32.

The publishers of the great *Handbuch der Regionalen Geologie* are issuing here a volume which does not form part of the *Handbuch*, but which deals more in detail with a single South American country, while the entire South American continent is treated in Volume VIII, section 5 of the *Handbuch*. A short chapter on the orography of Peru leads to the description of its stratigraphy which comprises 274 pages. This chapter is followed by one on the geological history of Peru; next follows a short chapter on the structure of the Cordillera; and later another one treats of the useful minerals. The final chapter deals with the earthquakes of Peru. A colored geologic map completes the volume. When we look at the latter and compare the space which is filled with colors with the much larger space which is left blank, we realize how incomplete the geologic maps of much of the world still must be, and how much work is left for the geologists of the future. Not even the entire coast line of Peru is completely mapped geologically.

The systematic description of the surface of the world from a geological point of view is a great accomplishment for which the publisher, Carl Winter, in Heidelberg, cannot be thanked enough. At the time when Eduard Suess wrote his *Antlitz der Erde* the task of describing the geology of the earth's surface was still within the reach of a single man. Now it has to be done by a large international staff of geologists, a task which has now been nearly completed in the *Handbuch.*

A. C. N.

Second Bibliography and Catalogue of the Fossil Vertebrata of North America. By OLIVER PERRY HAY. *Carnegie Institution of Washington, Publication No. 390,* Vol. I (1929). Pp. viii+916.

For a quarter-century Hay's original catalogue has been the constant companion of every paleontologist dealing with North American vertebrates, giving as it does a complete bibliography of all papers up to 1900 referring to any vertebrate fossil from this continent. The appearance of the first of the two new volumes containing the literature since that date is consequently an occasion for thanksgiving to workers in this field.

In plan the new work follows that of the original. A bibliographic

list arranged by authors occupies somewhat more than half of the first volume. This list is confined almost entirely to the literature published since 1900. Following this are the citations for each group, genus and species, arranged in a zoölogical classification. The present volume takes the catalogue through the amphibians; reptiles, birds, and mammals will be treated in the second volume, to be issued shortly.

It is an interesting commentary on the growth of the subject that the list of literature from the beginning to 1900 filled but some 250 pages while that of the last quarter-century occupies more than twice that space.

A. S. R.

Applied Geophysics in the Search for Minerals. By A. S. Eve and D. A. Keys. Cambridge University Press, 1929. Pp. x+253; text figs. 92.

After an introduction this very excellent book treats the following subjects in the order given: magnetic methods, electrical methods, electromagnetic methods, gravitational methods, seismic methods, radioactive and other methods. At the end of the book are attached Appendixes I and II, a very select bibliography of sixty-eight papers, and an Index.

In their Preface the authors define the technical level of the book, thus: "If this book holds rather too much sound theory for the practical man, and some excess of field work for the man of pure science, then it will not have altogether missed its mark." This statement is the key to their composition. The whole work displays an intimacy with both field and laboratory, a good perspective, and a keen discrimination between essentials and nonessentials. It is written in a lucid literary style which is intelligible to non-mathematical readers. In order to understand the derivations, however, the reader must be familiar with the calculus and with fairly advanced general physics. The authors have derived in full all the more difficult or unusual formulas instead of merely quoting formulas as is commonly done in works of this type. Some of the derivations are placed in the Appendixes at the end of the book.

All in all this is the best exposition of the principles of applied geophysics which the reviewer has seen.

M. K. H.

Glacial Geology and Geographic Conditions of the Lower Mohawk Valley. By ALBERT P. BRIGHAM. *New York State Museum Bulletin No. 280* (1929). Pp. 32; figs. 72. Map in pocket.

The report adds another to the long series of scholarly papers on the geology of New York State published by the University of the State of New York. About two-thirds of the book is devoted to glacial geology, and one-third to geographic conditions and man's relations thereto.

The text treats of the pre-glacial topography; the work due to the ice invasion, and materials left on its retreat; the pre-glacial lakes; drainage changes; and finally post-glacial erosion. The work of man and its relation to the geographic conditions is also historically treated. Early Indian trails and settlements, white explorations, settlements, towns, agriculture, industries, roads, and power, are all discussed as responses to the geographic conditions or efforts to use and control them.

Two major contributions in the physiographic section are: (*a*) the work on drumlins, drumloids, and linear topography, which shows these forms to be primarily due to ice erosion on the several materials encountered, drift, rock, gravels, etc.; (*b*) the demonstration, by study of striae, moraines, erratics, and outwash, that two lobes of ice pushed into this area from the east or great Hudson Valley, building a strong interlobate moraine nearly east and west across the area. It is to be hoped that Dr. Brigham's purpose to bring out another bulletin on the upper Mohawk Valley will be successfully achieved.

GEORGE D. HUBBARD

Carte Géologique du Massif du Mont Blanc. By PAUL CORBIN and NICOLAS OULIANOFF. Saint-Maur-des-Fossés: Imprimerie-Librairie G. Jacquart. Servoz-Les Houches, Chamonix, and Les Tines sheets, 1927–29. FR. 20 each.

Three splendid geologic maps (scale 1:20,000) of the French portion of Mont Blanc, each accompanied by a twenty-five page booklet with cross-sections and brief descriptions of the geology.

R. T. C.